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Testing the erosion resistance of vegetated floodbanks

Science project SC030228/SR2

Flood and Coastal Erosion Risk Management Research and Development Programme

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Executive summary

To provide a better understanding of the effect of management interventions on the performance of floodbanks, the Environment Agency ran bank vegetation management trials between 2003 and 2007 monitoring a number of parameters relating to vegetation performance under different management treatment options at three sites in East Anglia (Ely Ouse, Reach Lode and Billingborough). But although the resistance of different types and communities of vegetation to erosion was generally considered to be a vital part of floodbank management, no direct measurements of the erodibility of the vegetation cover by running water were included in the project's final plans.

To fill this gap, the Environment Agency asked L A B Coastal to develop and test a portable erosion measurement device (EMD) which could be used to test the erosion resistance of vegetated grass banks by subjecting small test areas to running water. This would determine the rates of soil erosion under different management treatment options in both summer and winter. From these data, management treatment options providing the optimum erosion protection could be recommended.

Eight of the 11 management treatment options were tested (seven at Ely Ouse), including the control. Three of the eight replicates in each treatment option had been selected for the vegetation monitoring. These were relocated and used for the erosion testing.

A total of 14 tests were carried out within each treatment option. Stratified random sampling was used to select the test areas within the replicate vegetation plots. This included nine test areas where the vegetation was, for that replicate, relatively poor with bare patches, and five where it was good. The testers concentrated on poor areas because these are the ones most likely to fail and are thus the weak points of any floodbank.

Each test area was 150 mm square. Water from the EMD was run across it at 4 ms^{-1} for a maximum of 30 minutes. Tests were curtailed if excessive erosion occurred or if problems arose further down the bank due to piping of water through faunal burrows and cracks.

During the summer series of tests, some geotechnical parameters in the wetted areas were also measured after the tests to examine the relationship between soil strength, erosion and other variables.

In general, the amount of erosion was variable within a treatment option but greatest within the poor areas.

Experience gained during these tests suggested that erosion could be affected by a number of different factors other than vegetation cover.

In a number of tests at Reach Lode, early erosion of loose soils was halted when a coherent clay layer was reached and further erosion was extremely slow. On the other hand, there were occasions when initially there was slow erosion in cohesive soils until a looser layer of soil was reached and the rate of erosion accelerated. A similar process was observed when a buried void (often in the form of an animal burrow) was reached and there was a rapid increase in the rate of erosion.

There was positive correlation between the amount of erosion and bare ground in the test areas. Bare ground occurs for a number of reasons:

- faunal activity (moles and voles);
- die-back due to shading by taller plants or uncut tufts of grass;

- die-back beneath dense clumps of arisings (terrestrial and aquatic) dumped on the bank.

In bare areas caused by shading or by faunal activity (e.g. molehills), the topsoil was often dry and loose, and so it was very readily washed away.

The proportion of relatively poor areas was considerable in all but the best parts of the most appropriate treatment options. So even if as short a section of floodbank as 10 m was overtopped, there is a high probability there would be several poor areas within it.

The present level of knowledge does not allow the mean depth of erosion likely to be critical for assessing the integrity of the floodbank to be defined, but the significant erosion under test suggests that potential weaknesses are present.

During the course of the erosion tests, a number of observations were made on botanical aspects that tied in with the erosion tests in different ways. It became clear that it was the proportion of ground covered by living vegetation at ground level that was important; taller grasses often concealed bare ground. However, a good covering of grass or other vegetation did not always result in little or no erosion. It was observed several times that erosion of the soil surface was occurring under the vegetation canopy even when this was close to the soil surface. In a few plots, there were stands where low-growing *Festuca rubra* formed a close interwoven cover to the soil and this appeared to be resistant to erosion.

The extent of bare ground is a relatively poor indicator of erosion resistance as this can be greatly affected by the quality of the bare ground, particularly in relation to the degree of compaction.

The test results using the EMD indicated that the management treatment options most likely to increase the erosion resistance of the floodbank were Treatment Options 1, 2, 5 and 7 (sometimes also Treatment Option 4). Treatment Option 1 at Reach Lode was affected by mole activity and Treatment Option 4 at Billingborough by voles. Treatment Option 2 showed the best performance overall, but the differences were small and not statistically significant.

The performance of the treatment options differed somewhat between sites and, to help assess the treatment options at each of the three sites, a scoring system was devised based on the average erosion recorded in summer and winter combined.

Test areas with the strongest soils generally recorded least erosion. The geotechnical measurements indicated that, overall, Treatment Options 2 and 5 were most consistent in having little erosion and strong soils. Treatment Option 1 was generally strong with little erosion except at Reach Lode, but this anomaly was probably due to intensive mole activity leaving areas of loose soil that were readily washed away. Under the more frequent mowing regimes (e.g. Treatment Options 1, 2 and 5), soil peds remain more tightly packed together and thus more resistant to erosion. The control, Treatment Option 11, was by far the weakest and most liable to erode.

It was concluded that at least one annual cutting is necessary by way of management. But although cutting at least once a year contributes significantly to bank performance, there is little direct evidence that more frequent cutting is beneficial. There is some suggestion that the removal of arisings may be beneficial when the frequency of cutting is low. This is mainly because the uneven distribution of a dense layer of arisings can lead to the development of bare patches. There is little evidence that high cutting frequencies contribute greatly to erosion resistance. From the point of view of bank erosion, the management of small mammal activity would appear to be a significant factor in some cases – though conservation issues are likely to arise.

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Contents

Appendices (in electronic form only)

List of Tables

List of Figures

1 Introduction

The value of a covering of living vegetation including its root system (particularly a cover of grass) in reducing the risk of water erosion of the soil surface has long been recognised. Floodbanks, which can be overtopped at times of high water levels, are a good example. To maintain optimum levels of erosion protection, it is vital to be able to define appropriate methods for determining the relative effectiveness of the vegetation cover maintained under different management treatment options.

1.1 Environment Agency's bank vegetation management trials

Recognising this, the Environment Agency set up a scoping study to investigate site selection and optimum study methods for full-scale trials. Bank vegetation management trials (Environment Agency 2009) were proposed which were designed:

> 'to provide an improved understanding of the effect of management interventions on the performance of the floodbanks and especially along lowland rivers under service conditions.'

These trials were conducted by consultants Ecology, Lands and People (ELP). The baseline surveys were completed in 2003 and the trials were concluded in 2007. The detailed results are given in *Flood Embankment Management Trials* (Environment Agency 2009).

The performance assessment was based primarily on monitoring the most important indicators of the performance of embankment vegetation. These indicators related to the vegetation composition and structure both above and below the soil surface and, in addition, a range of soil parameters.

At three sites in East Anglia (Ely Ouse, Reach Lode and Billingborough), 100-m long flood embankment reaches were divided into 11 experimental units, with each unit subjected to differing maintenance regimes (based on grass cutting frequency, removal of vegetation debris and used of herbicides). Physical (soil strength, moisture content), biological (vegetation cover, botanical and invertebrate biodiversity) and chemical (soil nutrients) parameters were recorded for each regime for five years. After the final year of the management trials, detailed erosion tests were also undertaken. These are the subject of this report.

The seven management treatment options (and the control) to which the floodbanks at the three locations had been subjected to during the vegetation management trials are summarised in Table 1.1. Full details are given in Environment Agency (2009).

The timing of the mowing was as follows:

- once per year: August;
- three times per year: April, July and September;
- six times per year: April, May, June, July, August and September.

The use of the weed wipe in Treatment Option 9 was to control the more vigorous and taller invasive weed species.

Table 1.1 Treatment Options used in the vegetation management trials.

Treatment Option	Annual mowing frequency	Arisings	Other management
1	Six times	Left	None
2	Three times	Left	None
4	Once	Left	None
5	Three times	Removed	none
7	Once	Removed	none
9	Once	Removed	Weed wipe twice
10[3]	Once	Left	Aquatic weed dumped and removed[1]
11	None	Not applicable	None [2]

Notes: [1] This was deposited on the river side of the ban and left for one week.
[2] The only treatment on the control plot was the cutting along the footpath.
[3] Not carried out at the Ely Ouse site (no aquatic weed cutting).

1.2 Addition of erosion testing

Although the resistance of different types and states of vegetation to erosion was generally considered to be a vital part of floodbank management, no direct measurements of the erodibility of the vegetation cover by running water were included in the final plans for the flood embankment management trials.

1.2.1 Development of a portable erosion measurement device

To fill this gap, the Environment Agency asked L A B Coastal to develop and test a portable erosion measurement device (EMD) that could be used to test the erosion resistance of vegetated grass banks by the principle of subjecting small test areas to running water to determine the point at which significant soil erosion occurs. The device used is pictured in Figure 1.1.

Figure 1.1 Erosion measurement device (EMD) used to test the erodibility of test areas on the floodbanks.

Previous attempts to measure erodibility in the field have either involved the installation of heavy equipment (Hewlett et al. 1987) or have been designed for testing only bare soil or mud rather than the vegetated soil surface itself (Tollhurst et al. 1999, Watts et al. 2003).

The portable EMD was developed by L A B Coastal specifically to test the erodibility of the vegetation–soil system. During proving trials, it was shown to be able to test this system effectively using water velocities of up to 8 metres per second (ms^{-1}) within a test area of 150 mm × 150 mm.

Details of the methods used for the erosion and vegetation measurements are given in Section 2.1 and the results in Section 4.

1.2.2 Geotechnical measurements

In discussions between L A B Coastal and the Environment Agency following the winter series of EMD tests, it was decided to enhance the scientific aspects of the summer series by including certain geotechnical measurements. These measurements were designed to investigate any relationship between the amount of erosion measured and the inherent strength of the topsoil. Only the soil surface (i.e. that immediately affected by erosion) was tested.

Details of the methods used for geotechnical measurements are given in Section 2.2 and the results in Section 5.

1.3 Soils surrounding the trial sites

Although river floodbanks are man-made, the soils of the surrounding land are of interest because some of the material used to build the banks may well have come from this land.

The soils on and around the banks at the trial sites are described in detail in Environment Agency (2009), so only some additional points are made here.

1.3.1 Ely Ouse, Cambridgeshire

At Ely, the surrounding land is mainly humified peat soils of the Adventurers' 1 Association (Soil Survey of England and Wales 1983). These soils sometimes have thin discontinuous layers of white shell marl present. The depth of peat varies but it can be up to five metres thick locally (Hodge et al. 1984). West of the river the land rises and the Peacock Association skirts the higher ground. Here, the peat has wasted away leaving a thin peaty or humose top over clay or clay loam subsoil. These soils formed in wet conditions and in fresh water.

1.3.2 Reach Lode, Cambridgeshire

The site at Reach is, like that at Ely, surrounded by Adventurers' 1 Association (Soil Survey of England and Wales 1983) and similar comments apply.

1.3.3 Billingborough Lode, Lincolnshire

At Billingborough, the situation is different with the site surrounded by soils of the Wallasea 2 Association (Soil Survey of England and Wales 1983). These are generally heavy clay soils developed in marine or estuarine alluvium, but there are some coarser textured soils (clay loam, silty clay loam, and silt loam), particularly on the ridges (rodhams) which are the sites of old creeks and are extensive (Hodge et al. 1984). There also appear to be thin gravelly layers exposed in the stream bed, although this material may have washed down from upstream. The soil on the bank at Billingborough has much material that appears to come from some of the local coarser sediments.

1.4 Project objectives

The objectives of the project were to:

1. Test the relative erosion rates at three sites in the Anglian Region of the Environment Agency (Ely Ouse, Reach Lode and Billingborough) using an EMD.

2. Test the relative erosion rates for summer and winter states of the vegetation.

3. Test the erosion rates on three replicate recording areas for each of the eight vegetation management regimes (seven treatments and one control), at six random points in each replicate (three over good vegetation cover and three over reduced cover).

4. Determine the relative differences in erosion rates resulting from the various methods of vegetation management.

5. Recommend which vegetation management treatment options provide the optimum erosion protection.

The fulfilment of these objectives was to be achieved by three specific working tasks. These are defined as:

- **Task 1 Erosion testing under winter conditions**. This should follow the methodology detailed above, when vegetation is at a 'winter minimum' (provisionally to be during January and February 2008).

- **Task 2 Erosion testing under summer conditions**. This should follow the methodology detailed above, when vegetation is at a 'summer maximum' (provisionally to be during June and July 2008).

- **Task 3 Data analysis**. Data analysis will comprise analyses of data collected during both testing periods and comparison with data collected during the five year vegetation management trials.'

Following discussions between the contractor and the Environment Agency following the completion of the winter series of testing, it was decided to enhance the scientific aspects of the summer series by including certain geotechnical measurements (see above).

2 Methods

2.1 Erosion and vegetation measurements

2.1.1 Specified procedure

The contract document specified the following procedure:

- The method used to test erosion rates must be adopted for all test sites.
- The methods must be replicable and provide statistically significant data sets.
- Trials using EMD equipment have determined the most appropriate methodology for this project.
- For each of the vegetation management treatment options at each site, tests need to be done on three replicate plots.
- Within each plot, stratified random sampling should be done to identify two or more distinct areas or strata (comprising good and poor vegetation cover) and their separate sampling and testing.
- Within each stratum, a minimum of three replicate sample points (up to an optimum number of five locations) for tests should be selected at random.
- The proportion of ground occupied by each of the strata needs to be recorded and the number of points susceptible to erosion estimated.
- The sampling procedure for the erosion testing at each sample point will be as detailed below:

i. Select the random sample point within the area of the vegetation recording plot of that replicate.

ii. Place quadrat (300 mm × 500 mm gridded into 100 mm squares) and photograph.

iii. Record vegetation height, bare ground, presence of any holes or cracks.

iv. Measure the profile of the central area with a profiler (long axis and transverse axis).

v. Set flume jet to be centred on the sample point.

vi. Run test for 30 minutes (4 ms^{-1}) with the jet at 7–8° from the horizontal.

vii. Record any erosion present (length, width and depth).

viii. Re-profile the central area and photograph.

2.1.2 'Good' and 'poor' areas

The prescribed method called for sample plots to be located in 'good' and 'poor' areas with regard to the vegetation cover within the vegetation recording plots.

- **'Good' areas** were defined as those areas where the plant (vegetation) cover at ground level was complete, or as near complete as possible, and thus with no bare soil visible or no soil with only a covering of unattached plant litter.
- **'Poor' areas** were defined as areas where there was a reduction in the plant cover at ground level. This was often tall vegetation or under dead vegetation.

If there was extensive bare soil, the areas of loose soil were used in preference to consolidated areas.

Recent molehills and vole hills and the actual animal burrows were avoided, though it was clear that some of the areas of loose bare soil could be attributed to previous animal activity.

The assessment of an area as good or poor was based entirely on the visible soil and vegetation and could not take any account of hidden holes and burrows close under the surface.

The terms 'good' and 'poor' with respect to the study as a whole were relative terms and not absolute. It became clear at an early stage that the poorest of the 'good' plots frequently had less vegetation cover than the best of the 'poor' plots within another management treatment option. The plots selected simply represented the best and the worst areas within that particular replicate in that particular treatment option.

2.1.3 Flume parameters

In all the tests, the flume was set perpendicular to the line of the floodbank on the riverside of the bank so that the water could be pumped from and returned to the river.

The shape of the lower part of the flume was designed to ensure that the water leaving the end of the flume was at a sufficiently low velocity that no erosion would be caused further down the bank as the water returned to the river.

Checks were made periodically on the flow of the waste water and the water velocities in this area were generally of the order of 1 ms^{-1} or less.

2.1.4 Changes to the original procedures

Three changes were made to the procedures originally specified.

The first related to the replication used in the erosion testing. In the first plot, tests were run in six erosion replicate plots (three on good or well-vegetated areas and three on poor areas with reduced vegetation cover). In the other two plots, four tests were carried out – one in a good area and three in poor areas. This gave a total of five good and nine poor areas tested per treatment option. This was fewer 'good' areas than had been originally proposed, but initial tests indicated that little or no erosion was taking place in such good areas and so it was decided to concentrate resources on the testing of poor areas. Statistically, the reduction in the replication for the good areas was generally adequately compensated for by the lower variability compared with the poor areas. Had the original procedure been followed, it would not have been possible to complete the programme of testing within the time available.

The second variation related to the water velocity used in the testing. This was originally specified at 6 ms^{-1}. Early tests indicated that this was unduly high and would have led to an unreasonable number of tests being cut short because of the extent of erosion being caused. Not only would this have caused unnecessary and undesirable damage to the floodbank, but it would also have increased the difficulties when comparing the different replicates of the test results. Accordingly the test velocity was reduced to 4 ms^{-1}. This resulted in less than 37 out of a total of 322 tests having to be curtailed because of excessive erosion during the winter series and 60 out of 322 in the summer; an overall proportion of 15 per cent. This corresponded to an average of two tests per treatment option causing significant erosion.

The third variation in test procedures was the replacement of the planned quadrat with the use of four aluminium pins (each 150 mm long and 6 mm in diameter pointed at one end and flat on top) to locate the test area and to act as reference points for the determination of the profile of the soil surface (Figure 2.1).

Figure 2.1 Test area marked out by the four marker pins which provide reference points for the recording of the profiles before and after the test.

2.1.5 Profiler

The profiler used was a 300-mm plastic profile gauge manufactured by Vitrex Ltd (Figure 2.2). This enabled the surface profiles of each test site to be determined at 1.5 mm intervals horizontally and drawn on a record sheet before and after running each erosion test.

Preliminary trials indicated that the profiles obtained were generally within an accuracy of ±1 mm. With the manufacture of 16 pins (see Section 2.1.3), four plots could be set out and recorded prior to the start of testing thus speeding up the whole process.

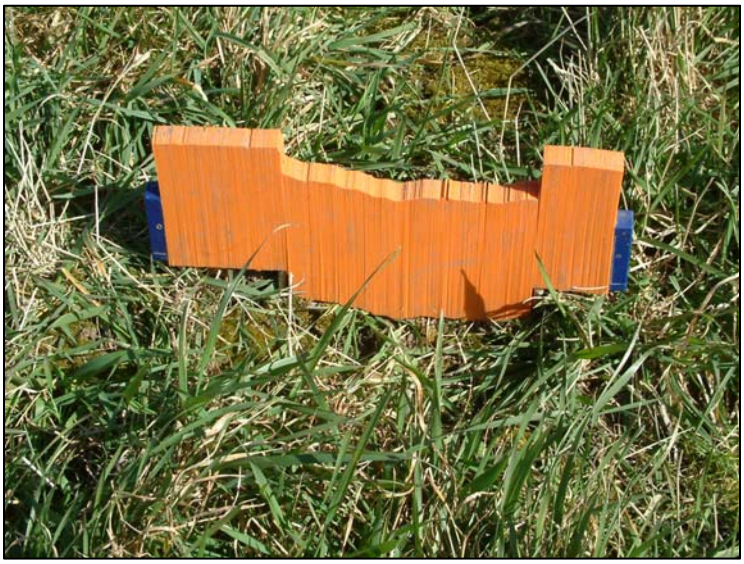

Figure 2.2 'Vitrex' plastic profile gauge used to record the profiles of each erosion plot before and after the test.

2.1.6 Extent of bare ground

As well as recording the depth of erosion within the test plots, the extent of bare ground within the 150 × 150 mm test area was also recorded both before and after the test.

The definition of bare ground used for this purpose was different from that used in the vegetation recording in the bank vegetation trials (Environment Agency 2009). The latter simply considered the static position of the proportion of ground not covered by vegetation or plant litter.

The immediate effect of running water over the surface (even at low speeds) would be to remove any plant litter and displace any vegetation not rooted within the plot. In view of this, any loose plant litter was removed from the plot and tall vegetation not rooted in the plot was moved to one side before the initial assessment of the percentage of bare ground and the initiation of testing.

Tall grass within or adjoining a plot was flattened in the direction of the water flow before the EMD was put in place. In a few of the plots, however, there were tall robust plant stems that would have prevented the placing of the EMD on the ground surface. These stems were cut just above ground level to permit the placing of the EMD but without affecting the pattern of water flow.

Many of the good plots showed some erosion and even the 'best' sites still showed some erosion. However, there were also a few of the poor plots that failed to show any erosion. Small differences between the two profiles could be attributed to the removal of superficial loose material without there being any significant erosion. Typically, good plots could show average apparent erosion of up to 2 mm while poor plots showed erosion typically 5–10 times greater.

2.1.7 Height of vegetation

The height of the vegetation around each of the test plots was also recorded.

Around each replicate plot, three measurements were made of the height of the vegetation as in the general studies.

Even when the test area was nearly devoid of vegetation, there could be comparatively tall vegetation around the test area.

2.1.8 Protocols

Protocols were set so as to increase the accuracy of the determination of the magnitude of erosion and the calculation of the cross-sectional area and the mean depth of erosion.

1. The areas between profiles before (black profile) and after (red profile) are calculated by use of a 5 × 5 mm squared grid on transparent film.
2. The grid is 150 mm wide and is overlaid on the profiles centred to include the area of maximum loss (if the recorded profile is more than 150 mm wide).
3. Where more than 50 per cent of the area is included, the number of complete squares between the two profiles is counted together with the number of squares.
4. If there has been erosion and apparent accretion* within a single profile, the difference is calculated and entered on the field sheet.
5. If the results from both profiles for a replicate test plot show erosion, each figure is entered on the field sheet and subsequently on the spreadsheet.
6. If the net result for the two profiles in a test plot shows accretion, erosion is taken as zero and is entered on the spreadsheet.
7. If the net result is erosion, this figure is used and entered on the spreadsheet.
8. Where the test has had to be terminated because of excessive erosion, the appropriate time is recorded on the field sheet.

*The before and after profiles are both taken over the flattened vegetation cover (if any) over the soil surface. Positive values apparently showing accretion are caused by a readjustment of the vegetation cover as a result of water flow (e.g. tall grass rooted outside the test area can be flattened into the test area thus raising the apparent ground surface level). Accordingly positive values were taken to represent no soil loss and zero was entered.

2.1.9 Soil field moisture content

Soil field moisture content was determined for the topsoil (0–50 mm) of each plot on the day the erosion was measured. This depth was chosen as being where most of the erosion would occur.

Samples were collected from areas that had not been subject to wetting by flow from the EMD and thus represented the condition of the soil at the start of each test.

Moisture was determined by heating the soils to constant dry weight at 220°C. The results for percentage moisture were calculated on a wet weight basis.

2.1.10 Length of tests

The tests were run for a standard length of 30 minutes. However, a test was terminated early if there was excessive erosion within the plot or when erosion threatened to dislodge any of the reference pegs. A test was also terminated if there was, or seemed likely to be, serious erosion beyond the plot itself or where bank stability was being threatened or seemed likely to be threatened.

2.2 Geotechnical measurements

These measurements were carried out during the summer session of EMD tests to investigate any relationship between the amount of erosion measured and the inherent strength of the topsoil. Only the surface soil (i.e. that immediately affected by erosion) was tested.

2.2.1 Equipment

Measurements were made with:

- a proving ring penetrometer (ELE International Ltd);
- a pocket penetrometer (York Survey Supply Centre);
- a shear vane (Pilcon Hand Vane Tester).

Previous work by the Environment Agency (2009) had concluded that the measurements made by these instruments correlated positively with one another.

2.2.2 Procedure

After each run of the EMD and once the profiles had been re-measured, geotechnical tests were carried out in the wetted soil around the 150 × 150 mm test area; eroded areas were avoided. It was not possible to locate the geotechnical measurements in the same place with regard to the test area as the water flow and erosion pattern was different each time.

Three measurements were made around each test area with each instrument.

Any litter and other plant material obscuring the soil surface were cleared away before measurements could be made.

2.2.3 Comments on equipment use

Proving ring penetrometer (PRP)

The proving ring penetrometer was the instrument easiest to use in a reliable way and seems to have given the most meaningful results. The cone was pressed into the soil until the top was level with the ground surface.

Occasional difficulties arose when there were voids in the soil, possibly due to faunal activity (mainly vole species and moles); any zero readings from these were disregarded and another reading taken.

Pocket penetrometer (PP)

When using the pocket penetrometer, there was a different problem due to the small diameter of the probe pushed into the soil. The soil structure beneath the sward was often a loose, fine to medium angular blocky (Hodgson 1997). This made it quite difficult to get meaningful readings with the pocket penetrometer as these small peds are, in themselves, quite hard, but are loosely aggregated and so very weak as a whole. Again, any zero readings where the soil aggregates were simply pushed aside by the penetrometer were disregarded and the measurement repeated.

Shear vane (SV)

With the shear vane, the vanes were pushed in until just below the soil surface. As with the proving ring penetrometer, the instrument sometimes entered a void and zero measurements were disregarded and the test repeated elsewhere.

2.2.4 Data recording and analysis

The PRP readings were converted from the scale reading to kilopascals (kPa) using a conversion table. The SV read directly in kPa and the PP in kg cm^{-2}.

These data were then entered into Microsoft® Excel and Minitab® spreadsheets.

For each of the three sites, these data were then plotted by management treatment option to see if there was any relationship to soil geotechnical properties.

The data were also plotted by management treatment option but split to show any differences between test areas with ‘poor’ and ‘good’ ground cover. ‘Significant’ differences are at 95 per cent confidence level ($p<0.05$).

3 Progress of fieldwork

3.1 Winter series of tests

Winter fieldwork was carried out between 3 January and 7 March 2008 (a total of 36 days in the field). The Ely Ouse site was tested between 3 January and 24 January, Reach Lode between 25 January and 15 February, and Billingborough between 16 February and 7 March.

Work at Ely Ouse was interrupted a couple of times by heavy rain and at Reach Lode work was abandoned one day as gale force winds made working by the water's edge hazardous. One day was lost as a result of structural failure of the mounting of the motorised water pump. Some maintenance was also required on the flume from time to time, but no significant delays were caused.

During the winter series of tests, eight of the original 10 treatment options were tested at Reach Lode and Billingborough, and seven at Ely Ouse. This was in accordance with the management treatment options used in the vegetation monitoring completed by ELP (Environment Agency 2009). Within each treatment option, the three random replicate plots and the vegetation recording areas used by ELP were used for the erosion testing.

3.2 Summer series of tests

The summer series of tests was performed in two separate blocks. To fit in with the schedules for the mowing management, it was planned to test Treatment Option 1 before the scheduled June cut and additionally to test Treatment Options 2 and 5 before their scheduled July cuts. The testing programme was thus set to run from 29 May to 11 June and from 30 June to the beginning of August.

Treatment Options 1 and 2 at Ely Ouse and Billingborough were tested during the first period, with Plot 5 at both sites being tested before the July mowing. Unfortunately because of difficulties with plot locations at Reach Lode, the May mowing was not completed until the end of May and accordingly the May tests at Reach Lode were delayed until the second block of testing was started in late June.

With the greater day length, the summer tests were completed in 31 days although four days were lost at Reach Lode during the problems there with the plot markings and a further day was lost to inclement weather at Billingborough.

The schedule called for a total of 98 tests at Ely Ouse and 112 tests at each site at Reach Lode and at Billingborough during the winter and again during the summer seasons, i.e. a total of 644.

3.3 Curtailment of tests

The tests were scheduled to run for 30 minutes (see Section 2.1.10). Curtailment of the test due to excessive erosion (or the likelihood of it) only occurred in one plot at Ely Ouse during the winter session and not at all during the summer. One replicate plot could not be recorded because the very vigorous growth of the vegetation prevented the placing of the flume.

At Reach Lode, curtailment occurred in one of the plots with poor plant cover in the winter and 15 of the plots with poor cover during the summer. In the summer, a mistake by the mowing contractors meant that two replicates of one treatment option had to be abandoned.

At Billingborough, tests in the winter series had to be curtailed in 31 of the poor plots; four of the plots with good cover showed heavy erosion and these tests also had to be curtailed. During the summer at Billingborough, 45 of the tests in poor plots and 12 tests on good plots had to be shortened.

In addition, there was a slippage towards the base of the river bank in Treatment Option 2, Replicate 4 at Billingborough during the winter and the rest of the tests on this section had to be abandoned.

3.4 Final number of tests

The schedule called for a total of 98 tests at Ely Ouse and 112 tests at each site at Reach Lode and at Billingborough during the winter and again during the summer seasons, i.e. a total of 644. Of this scheduled total:

- four tests were not started because of the very vigorous growth of vegetation in the summer at Ely Ouse (Treatment Option 4, Replicate 3);
- eight tests at Reach Lode (Treatment Option 2, Replicates 4 and 5) in the summer were not possible because of the mowing errors in the management of certain treatment options;
- nine tests at Billingborough were lost because of the bank slippage in the winter and the risk of its re-activation in the summer (Treatment Option 2).

Thus a total of 623 tests were performed in total.

Approximately 1,300 photos were taken of test plots before and after the test procedure had been completed.

4 Erosion and vegetation results

Three parameters were measured during the erosion trials on the bank vegetation:

- depth of erosion (as indicate by the change in profile) (see Section 4.2);
- height of the vegetation (see Section 4.3);
- extent of bare ground (see Section 4.4).

The results for these parameters are considered by plot and by treatment option and, in particular, in relation to the control (Treatment Option 11).

4.1 Background information

Once the few initial problems had been overcome the equipment performed well. The tests were made and the data were collected without any major difficulties being encountered.

The unusually dry winter enabled the winter series of tests to be completed more or less to schedule with few delays through inclement weather. The delays experienced during the summer series were mainly those at Reach Lode relating to the management of certain treatment options. The main problem with wet weather was in connection with the photographing of the plots before and after each test, and this needed at least a few short dry periods.

4.1.1 Soil moisture content

Not surprisingly the winter soil moisture contents were higher than those in the summer (Table 4.1), though the difference was lower than might be expected as a result of the drier than normal winter and wetter than normal summer.

Table 4.1 Soil moisture content during the testing periods.

Site	Soil moisture content at 0–150 mm (% fresh weight)	
	Winter	**Summer**
Ely Ouse	46.0 ± 1.6	35.5 ± 2.2
Reach Lode	43.0 ± 1.9	35.2 ± 2.0
Billingborough	27.6 ± 1.2	24.2 ± 1.9

Notes: All values are given together with the 95 per cent confidence limits (p=0.05).

Weather during the winter sampling was particularly dry and during the summer it was particularly wet. At Ely Ouse and Reach Lode, soils were 5–10 per cent drier in summer than in winter. At Billingborough, however, there was little seasonal change and moisture contents were lower than at either of the other two sites. This probably reflects the coarser textured topsoils common on the bank at Billingborough.

These differences in soil moisture probably did not have a direct effect on the results of the erosion tests as even the drier soils wetted up rapidly at the start of each test; the exception was the dense clay layers, which proved to be highly resistant to erosion by flowing water. The effects of soil moisture levels on soil strength are dealt with more fully in the Section 4.2. The enhanced moisture levels during the summer may well have had an indirect effect on the resistance of the vegetation to erosion, particularly in the way that the usual die-back of summer during late June through to August or even September did not occur. However, it is likely that the more favourable growing conditions during the summer affected all the treatment options in the same way, with the vegetation playing an enhanced role with regard to erosion resistance.

4.1.2 Differences in erosion between areas and sites

The erosion tests overall showed a marked difference between the areas assessed as ‘good’ and ‘poor’ in both summer and winter.

The good areas generally showed an equally high resistance to erosion in summer and winter, while the poor areas generally eroded more readily in the winter. At all times, the rate of erosion of the poor areas was several times that of the good areas.

The erodibility of the test areas was broadly similar at Reach Lode and Ely Ouse, but the rates were significantly higher at Billingborough. Indeed the rates of erosion of good areas at Billingborough were often close to that measured in the poor areas at Ely Ouse or Reach Lode.

These differences can be highlighted by looking at the number of tests terminated before the end of the full 30-minute test period (Table 4.2). This table highlights the generally very low erosion resistance of nearly all of the poor plots at Billingborough, as well as some of the plots initially assessed as ‘good’. The erosion of some of the poor plots at Reach Lode mainly occurred in one treatment option where there had been significant mole activity disturbing the vegetation cover; for example, in the vegetation recording plot of Treatment Option 1 at Reach Lode, there was one new molehill in every 1.3 m^2.

Table 4.2 Numbers of tests terminated early because of excessive soil erosion.

Site location	Winter		Summer	
	Poor area	Good area	Poor area	Good area
Ely Ouse	1	0	0	0
Reach Lode	1	0	15	0
Billingborough	31	4	45	0

The comparative plot performance at Ely Ouse, Reach Lode and Billingborough can also be summarised by considering the performance of the areas assessed as good and poor in relation to their actual performance under test. If it had been possible to assess the erosion resistance of the test areas accurately on purely vegetational characteristics, it might have been expected that all of the areas assessed as poor and none of the good areas would have eroded. However this was clearly not the case (Table 4.3).

Table 4.3 Number of occasions where plots selected as 'good' showed erosion or plots selected as 'poor' failed to erode during the summer or winter season.

Site location	Winter		Summer	
	Good area	Poor area	Good area	Poor area
Ely Ouse	9	1	14	13
Reach Lode	16	0	14	17
Billingborough	28	0	34	0

The erosion of the 'good' plots reflects the difficulties in finding areas with dense plant cover over the surface of the soil. This was particularly the case at Billingborough, where the proportion of bare ground was greatly increased both by vole activity and by the die-back of large annual plant species.

The failure of plots selected as 'poor' to erode (Ely Ouse and Reach Lode during the summer) reflects the effects of the combination of mowing producing denser swards and greater soil strength in the drier summer months. The similarity of the general erodibility at Ely Ouse and Reach Lode sites is further underlined by the results presented in Table 4.3.

This problem could also be seen in the control plots (Treatment Option 11) where the lack of management resulted in a distinct shortage of good areas within the vegetation monitoring areas (Table 4.4). The situation was particularly true at Billingborough, where in both winter and summer, more than half the good plots showed erosion. However, only a few poor areas failed to erode within this treatment option. Overall the number of good plots that failed to erode under test reflects well the relative strengths and weaknesses of the three sites in the 'control' treatment option.

Table 4.4 Number of occasions when 'control' Treatment Option 11 where plots selected as 'good' showed erosion or plots selected as 'poor' failed to erode during the summer or winter season.

Site location	Winter		Summer	
	Good area	Poor area	Good area	Poor area
Ely Ouse	2	0	4	0
Reach Lode	3	0	1	2
Billingborough	5	0	5	0

4.2 Depth of erosion

The control plots as a whole (Treatment Option 11) generally showed a lower erosion resistance that most of the treatment plots. However, there was a big difference between Billingborough on one hand and Ely Ouse and Reach Lode on the other. This was also reflected in the treatment plots.

4.2.1 'Poor' plots

In the plots assessed as being poor, less erosion was generally experienced during the winter months than the summer (Figures 4.1 and 4.2).

If serious erosion is considered as erosion to a mean depth of more than 75 mm, then this was detected only at Billingborough and then only at Treatment Options 11 and 4 in the poor plots during the winter (Figure 4.1). The former was the untreated control. Treatment Option 2 at Billingborough was where there was a slippage of the lower bank during testing and the site had to be abandoned (see Section 3.3); it was also much affected by small mammal burrows.

At Billingborough, winter erosion in poor plots was significantly lower in Treatment Options 1, 2 and 7 than in Treatment Option 11. At Ely Ouse and Reach Lode, all the treatment options showed comparatively little erosion but, in general, Treatment Options 2, 4, 5 and 7 showed less erosion than Treatment Option 11 – although the differences were not statistically significant.

Overall, winter erosion was least in Treatment Options 1, 2, 4, 5 and 7 although, at Billingborough, Treatment Options 4 and 5 showed more erosion than elsewhere.

The greatest erosion in poor areas was seen in Treatment Option 11 during the winter (Figure 4.1) but, at least in some plots, there was rather more erosion during the summer months (Figure 4.2).

- At Billingborough, Treatment Options 1, 2 and 5 showed significantly more resistance to erosion than Treatment Option 11. Neither Treatment Options 9 nor 10 differed significantly from the control (Treatment Option 11).
- At Ely, Treatment Options 1, 2, 4, 5 and 7 were significantly better than Treatment Option 11.
- At Reach Lode, only Treatment Options 4, 7 and 10 were more resistant to erosion than the control. However, Treatment Option 5 was marginally more resistant and Treatment Option 1 had been seriously affected by the activities of moles. Two of the tests unaffected by moles showed erosion resistance comparable to that seen at Ely Ouse and at Billingborough.

Taking the summer and winter results together, the greatest resistance to erosion was under Treatment Options 1, 2, 4, 5, and 7.

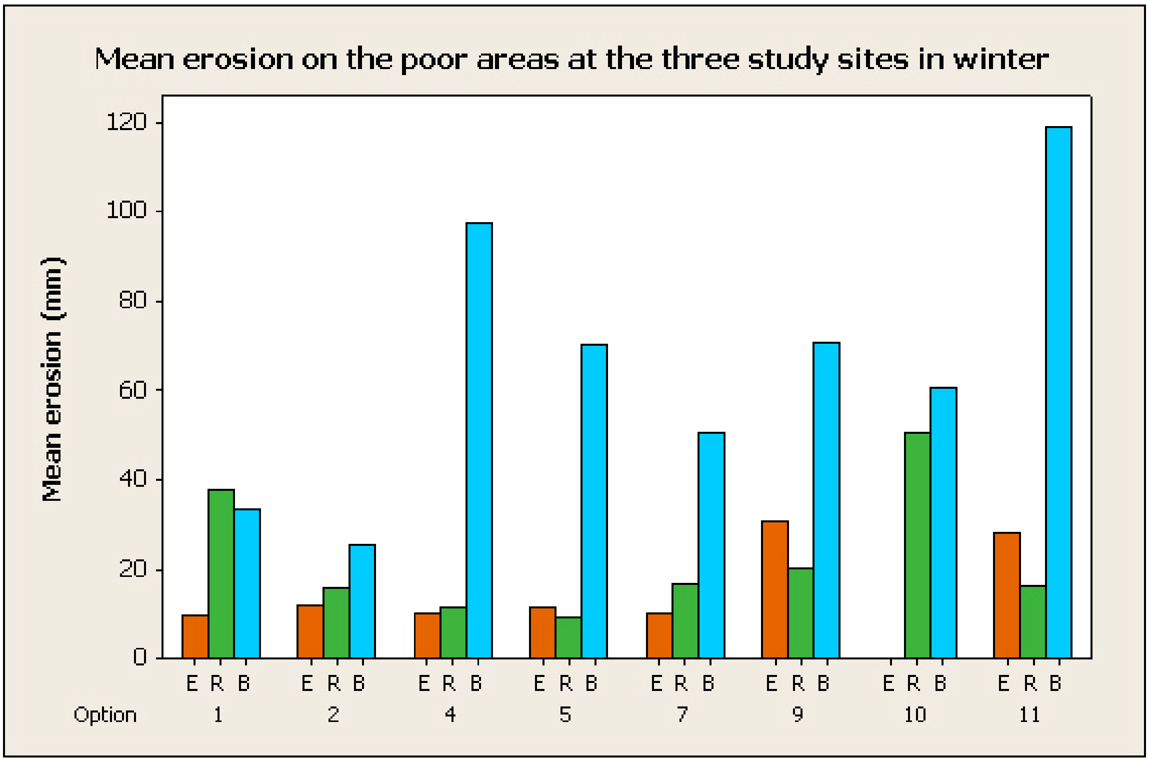

Figure 4.1 Mean erosion in poor areas at the three study sites in winter (E = Ely, R = Reach, B= Billingborough).

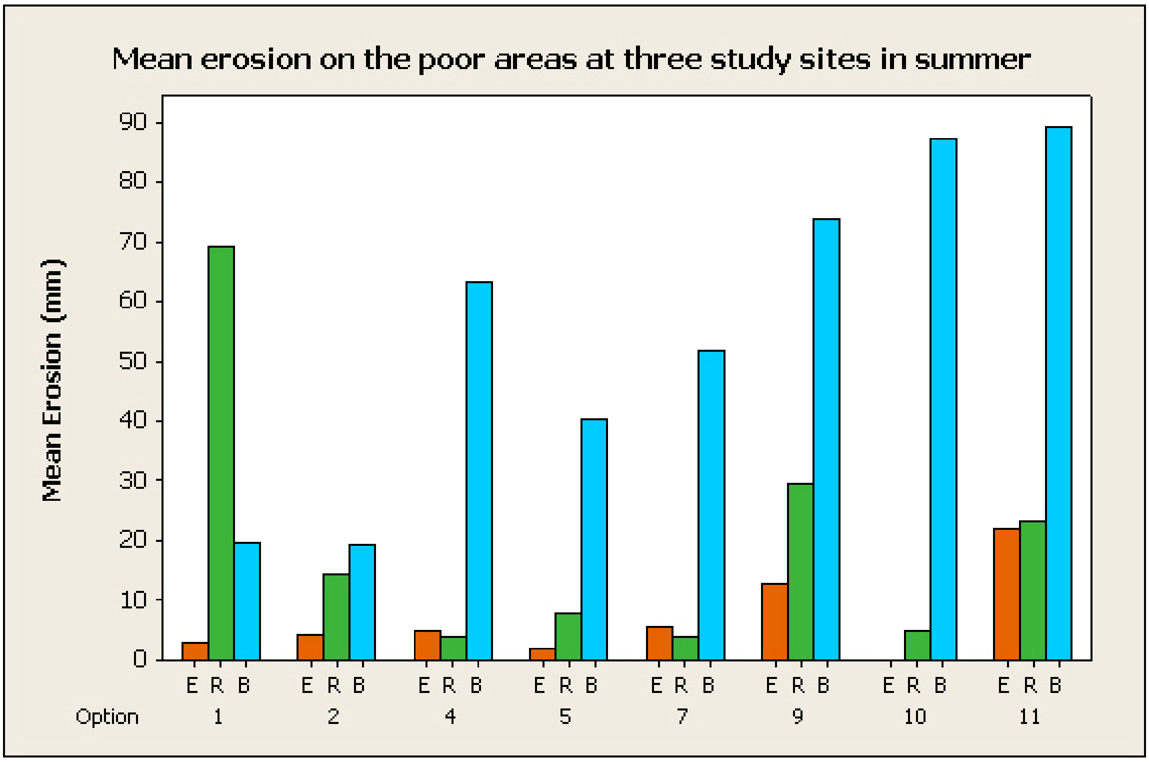

Figure 4.2 Mean erosion in poor areas at the three study sites in summer (E= Ely, R= Reach, B= Billingborough).

4.2.2 ‘Good’ plots

In the plots assessed as being good, there was much less erosion than might have been expected, although Billingborough still showed significant erosion in Treatment Options 4 and 11 in the winter (Figure 4.3) and in Treatment Options 4, 7, 10, and 11 in the summer (Figure 4.4). Erosion was much less at the other sites and with the other treatment options. At both Ely Ouse and Reach Lode, none of the treatment options differed significantly from the control (Treatment Option 11).

Overall, resistance to erosion was shown particularly by Treatment Options 1, 2 and 7 and also, although rather less, by Treatment Options 4, 5, 7, 9 and 10.

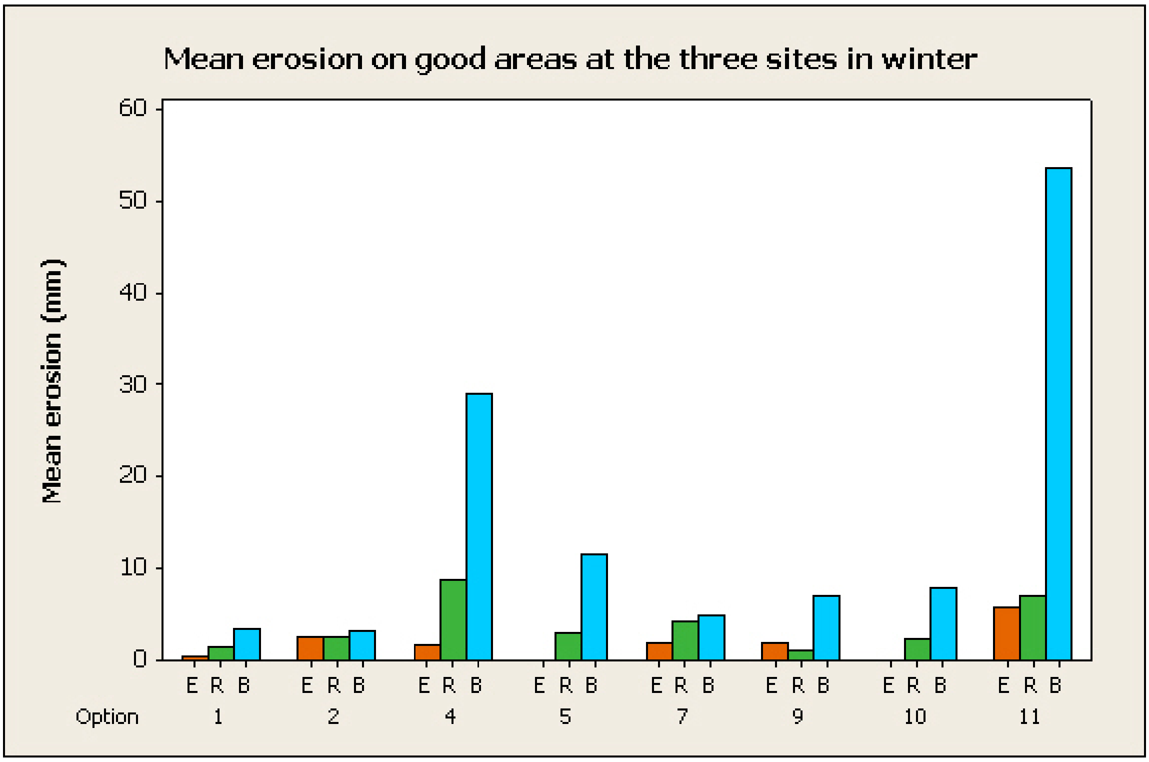

Figure 4.3 Mean erosion in good areas at the three study sites in winter (E = Ely, R = Reach, B = Billingborough).

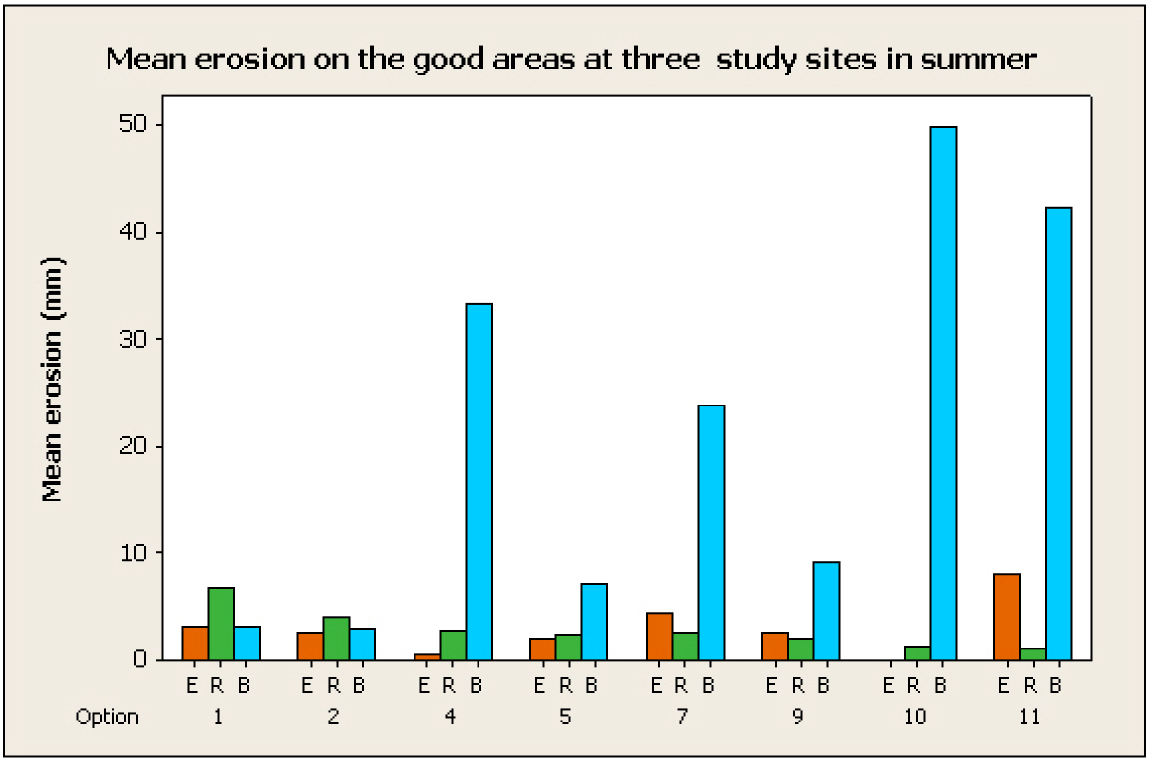

Figure 4.4 Mean erosion in good areas at the three study sites in summer (E= Ely, R = Reach, B = Billingborough).

4.2.3 Overall

Taking all these erosion test results together, they indicate that the greatest resistance to erosion was shown by Treatment Options 1, 2, 4, 5, and 7, although Treatment Options 4 and 5 were weaker at Billingborough.

4.3 Vegetation height

4.3.1 'Poor' plots

The mean vegetation height around the poor plots was very much lower during the winter than the summer, with only limited regrowth in the treatment options cut in September (Figures 4.5 and 4.6).

Nevertheless the winter vegetation height was significantly lower than the control (Treatment Option 11) in Treatment Options 1, 2, 5, and 7 at Ely and Treatment Options 2, 4 5 and 7 at Reach Lode. At Billingborough, none of the treatment options were significantly lower then the control (Figure 4.5).

In the summer, the mean vegetation height around the poor plots was lower than the control in Treatment Options 1, 5, 7, and 10 at Ely Ouse, Treatment Options 1, 2, 4, 7, and 10 at Reach Lode, and Treatment Options 1, 4, and 10 at Billingborough (Figure 4.6).

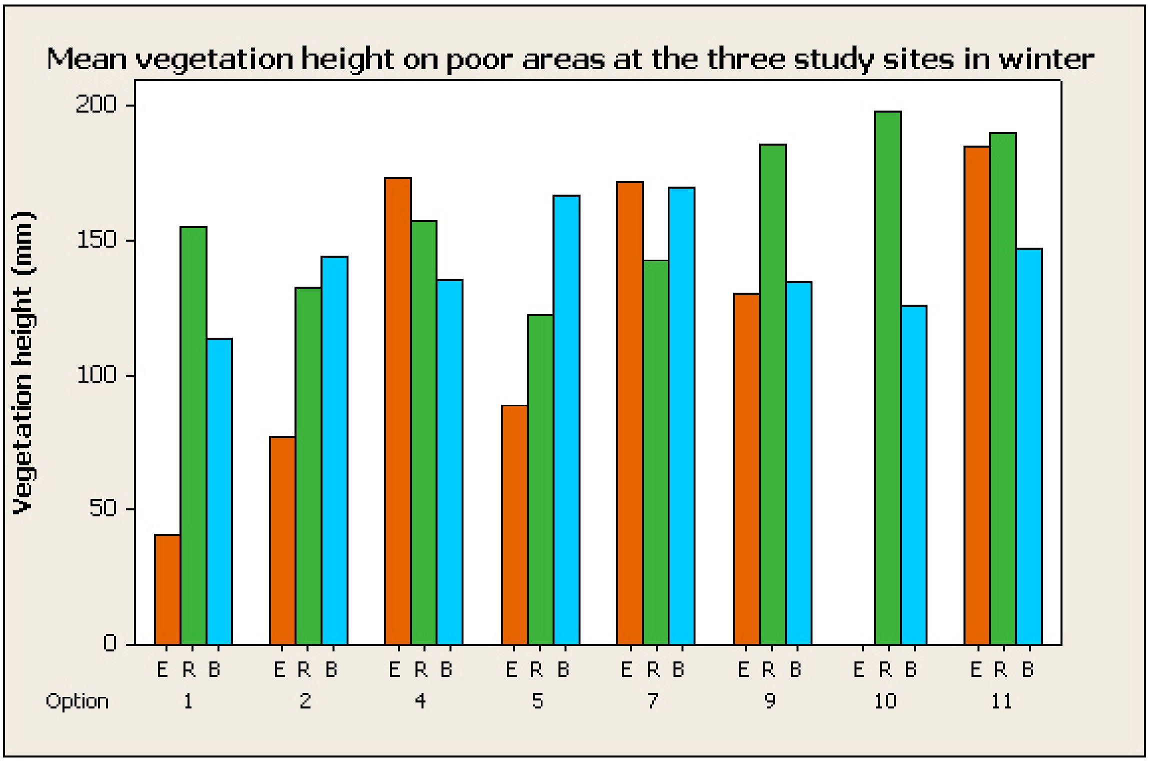

Figure 4.5 Mean vegetation height on poor areas at the three study sites in winter (E = Ely, R = Reach, B = Billingborough).

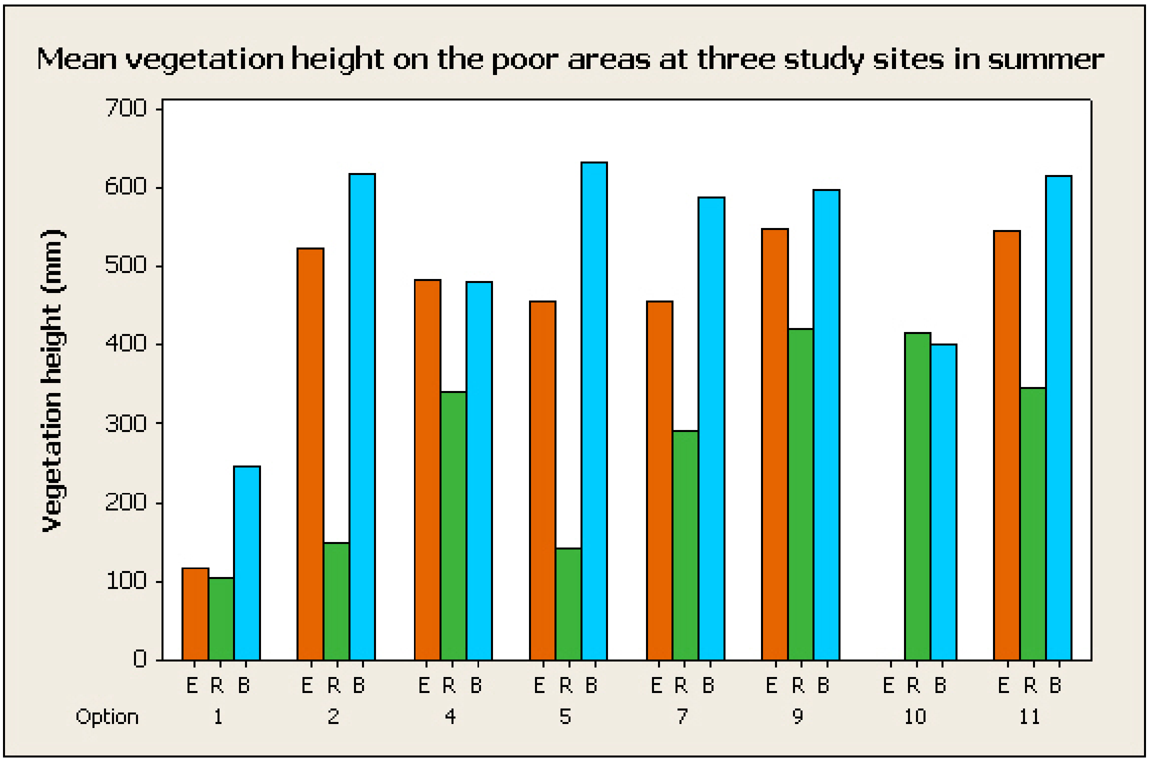

Figure 4.6 Mean vegetation height on poor areas at the three study sites in summer (E = Ely, R = Reach, B = Billingborough).

4.3.2 'Good' plots

At Ely Ouse and Billingborough, the vegetation around good plots during the summer in Treatment Option 1 was significantly lower than in the other treatment options (Figure 4.7), possibly reflecting the beneficial effects of mowing six times per year. At Reach Lode, however, Treatment Options 1, 2, 4, 5 and 7 were lower than elsewhere – although only Treatment Options 1, 2 and 5 were significantly lower than the control (Treatment Option 11).

The vegetation heights around the good plots were all much reduced during the winter months (Figure 4.8). At Ely Ouse, Treatment Options 1, 2, 5 and 9 were significantly lower than the control. At Reach Lode, only Treatment Option 5 was significantly lower while, at Billingborough, only Treatment Option1 was significantly lower than the control.

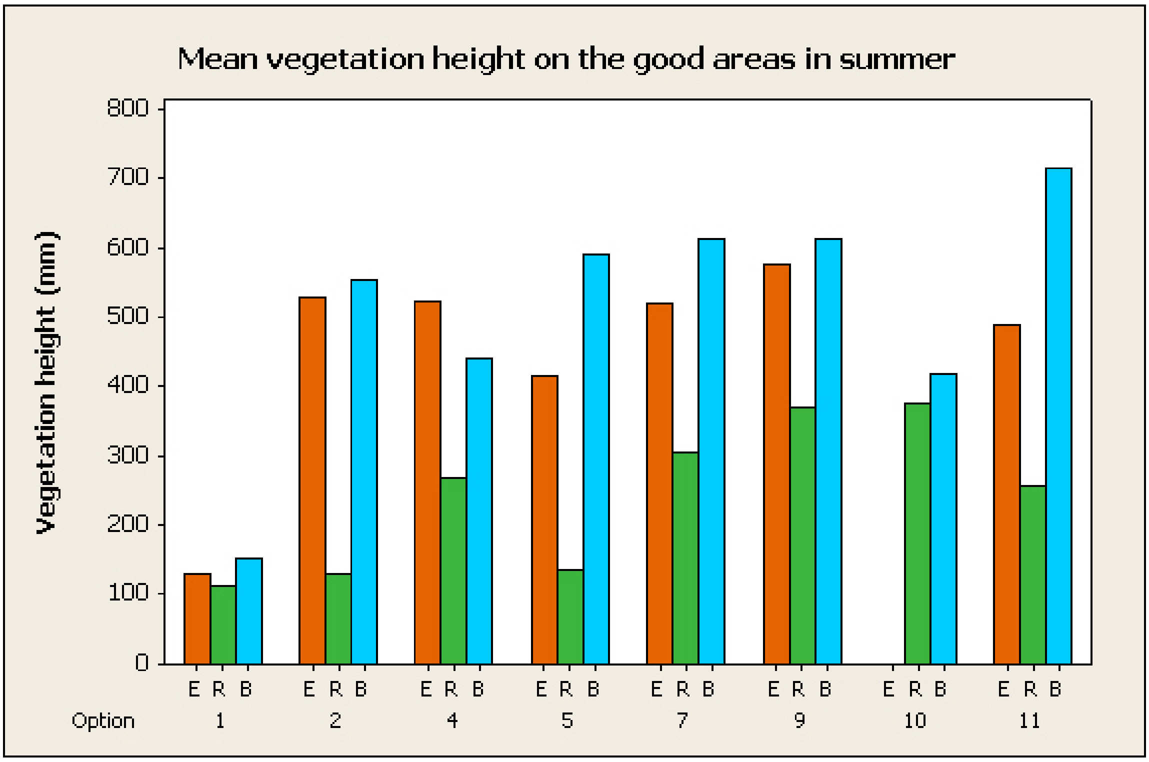

Figure 4.7 Mean vegetation height in good areas at the three study sites in summer (E = Ely, R = Reach, B = Billingborough).

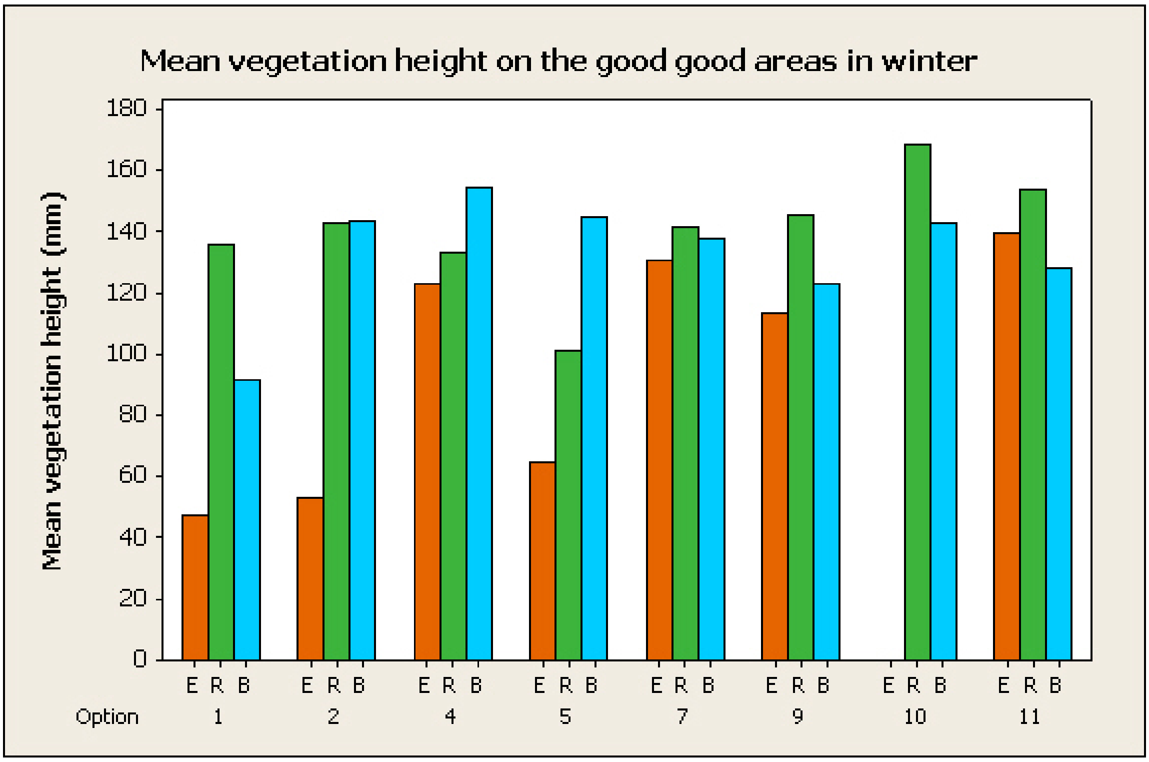

Figure 4.8 Mean vegetation height in good areas at the three study sites in winter (E = Ely, R = Reach, B = Billingborough).

4.4 Extent of bare ground

4.4.1 'Good' plots

In the plots assessed as good, there was little bare ground in the winter and what there was, was mostly at Billingborough (Figure 4.9).

In the summer, however, there was some bare ground at all the plots at Billingborough with the least at Treatment Options 1, 2, and 4 (Figure 4.10).

The high proportion of bare areas at Billingborough reflects the combination of vegetation and soil interactions and animal activity.

There was also some bare ground at Treatment Options 2 and 9 at Ely, but none in any of the treatment options at Reach Lode.

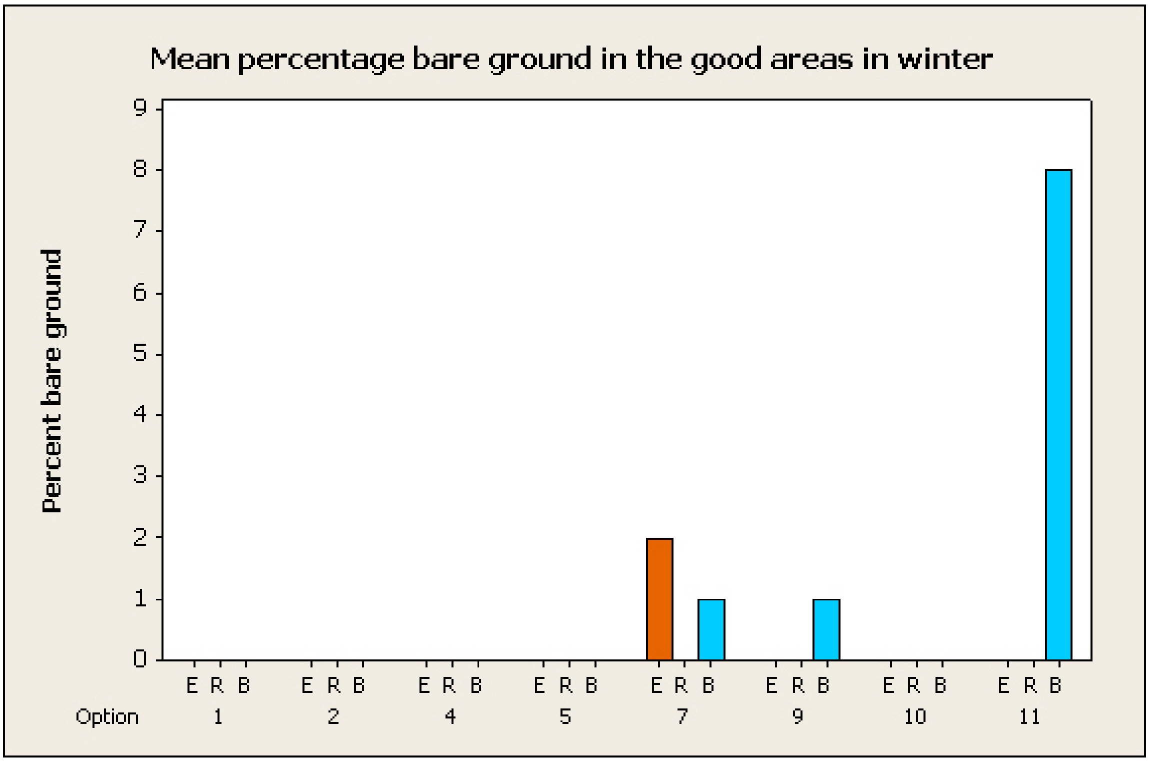

Figure 4.9 Mean percentage bare ground in good areas at the three study sites in winter (E = Ely, R = Reach, B = Billingborough).

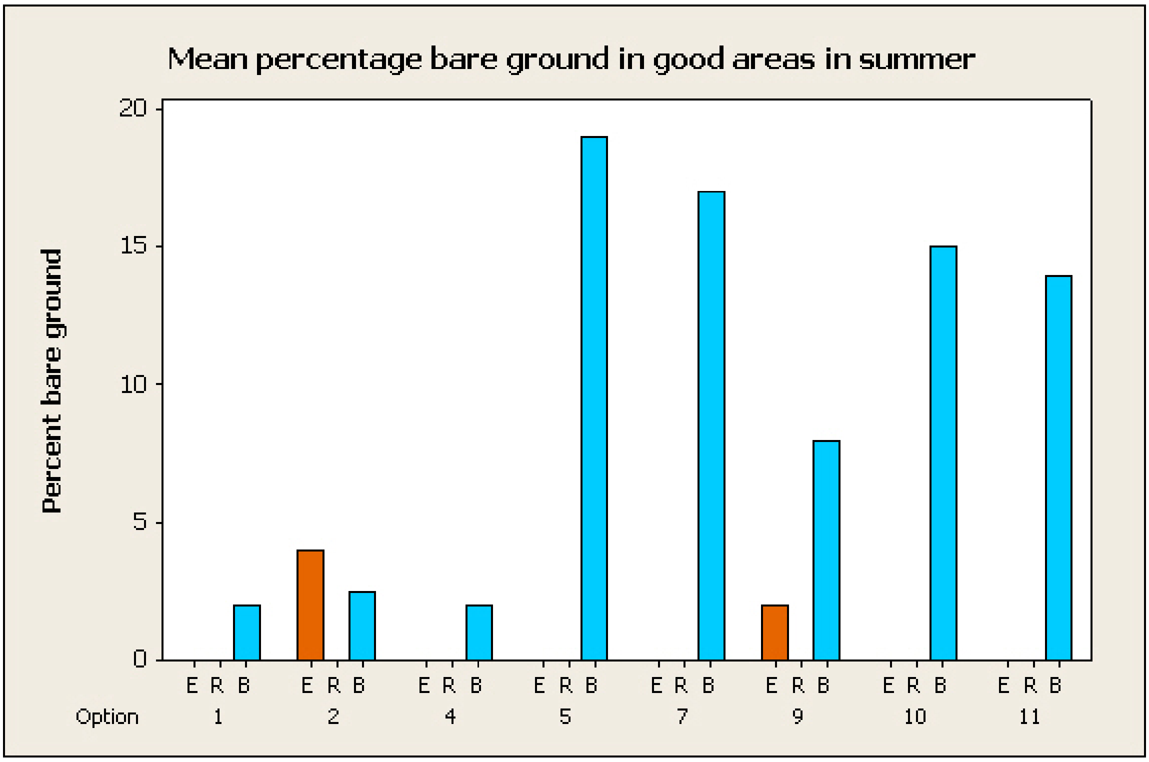

Figure 4.10 Mean percentage bare ground in good areas at the three study sites in summer (E = Ely, R = Reach, B = Billingborough).

4.4.2 'Poor' plots

In the plots assessed as poor there was extensive bare ground in both summer and winter (Figures 4.11 and 4.12).

With the exception of Treatment Option 1 at Ely Ouse, all plots had bare ground in excess of 40 per cent and, at Treatment Options 7, 9 and 11, it was over 70 per cent.

There was considerably less bare ground during the summer with less than 50 per cent occurring in Treatment Options 1, 2, 5 and 7 at Ely Ouse, and in Treatment Option 4 at Reach Lode.

Overall there appeared to be least bare ground at Ely and most at Billingborough, with Reach Lode being intermediate. Again Reach Lode would have had less bare ground had it not been for the activity of moles, while much of the bare ground at Billingborough could be attributed to vole activity.

There are two sources of data available on the extent of bare ground:

- the data from the sample areas within the vegetation recording plots as recorded during the flood embankment management trials (Environment Agency 2009);
- the data recorded by L A B Coastal as precursors of the erosion tests.

The latter data were taken within the erosion recording plots selected within each of the good and poor areas.

The two data sets can not be compared directly because of the different methodologies used (they were also obtained at different times of the year). But when the percentage of bare ground is compared with the erosion test results at the three sites, there is a statistically significant relationship between the mean depth of erosion and the percentage of bare ground. However, when comparing the various treatment options within each site, there is little correlation between the proportion of bare ground and the depth of erosion. This is not entirely surprising as between site comparisons are based on large data sets from wide areas and the comparisons between treatment options are based on very limited data sets.

The actual quality of bare ground also has implications regarding the percentage of bare ground. Part of the explanation for the poor erosion resistance at Billingborough was the high proportion of the bare ground, which had very loose soils, compared with the often well-compacted areas of bare soil at Reach Lode and Ely Ouse. The higher mean erosion depth at Reach Lode compared with Ely Ouse can largely be attributed to the mole activity at the former.

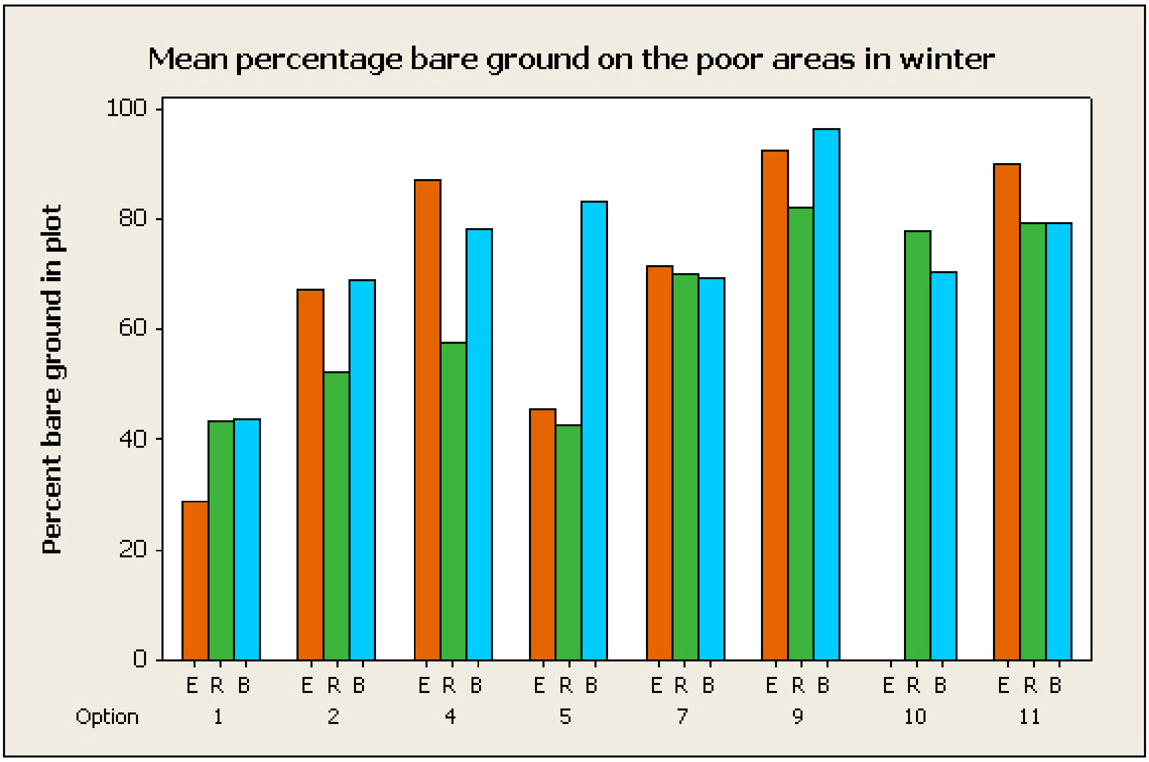

Figure 4.11 Mean percentage bare ground in poor areas at the three study sites in winter (E = Ely, R = Reach, B = Billingborough).

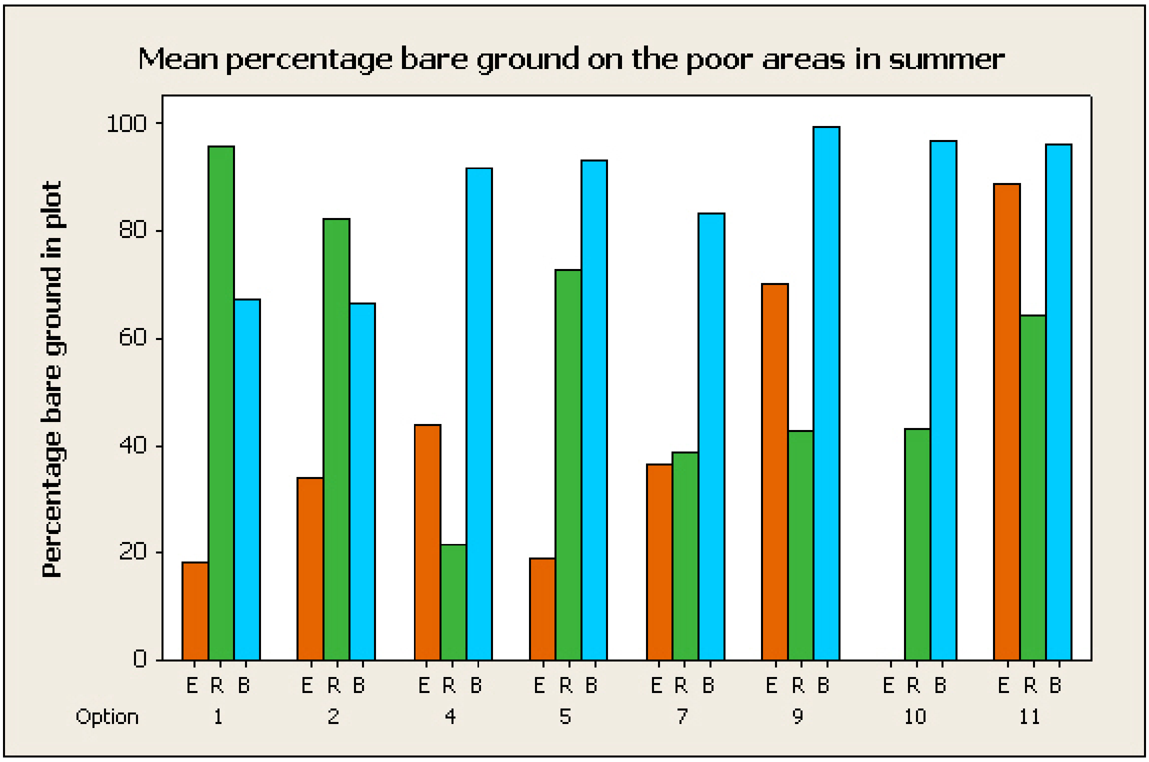

Figure 4.12 Mean percentage bare ground in poor areas at the three study sites in summer (E = Ely, R = Reach, B = Billingborough).

4.5 Termination of tests

The early termination of tests when there was excessive erosion is discussed in Section 4.1.1. The difficulties associated with estimating the degree of erosion without stopping the test and removing the flume meant it was not possible to stop at a specific degree of erosion and, in some cases, the excessive erosion was occurring outside the perimeter of the test plot itself. Consequently the depth of erosion within the test area at the end of the shortened test varied.

This raised the interesting question as to how much more erosion would there had been if the test had been allowed to run the full 30 minutes. Accordingly in one plot at Ely Ouse, estimates of the depth of erosion were made every five minutes for the duration of the 30-minute run of the test. The results showed that, although there was considerable variation in the rates of erosion during the course of a test, there was a degree of linearity in the rate of erosion (Figure 4.13).

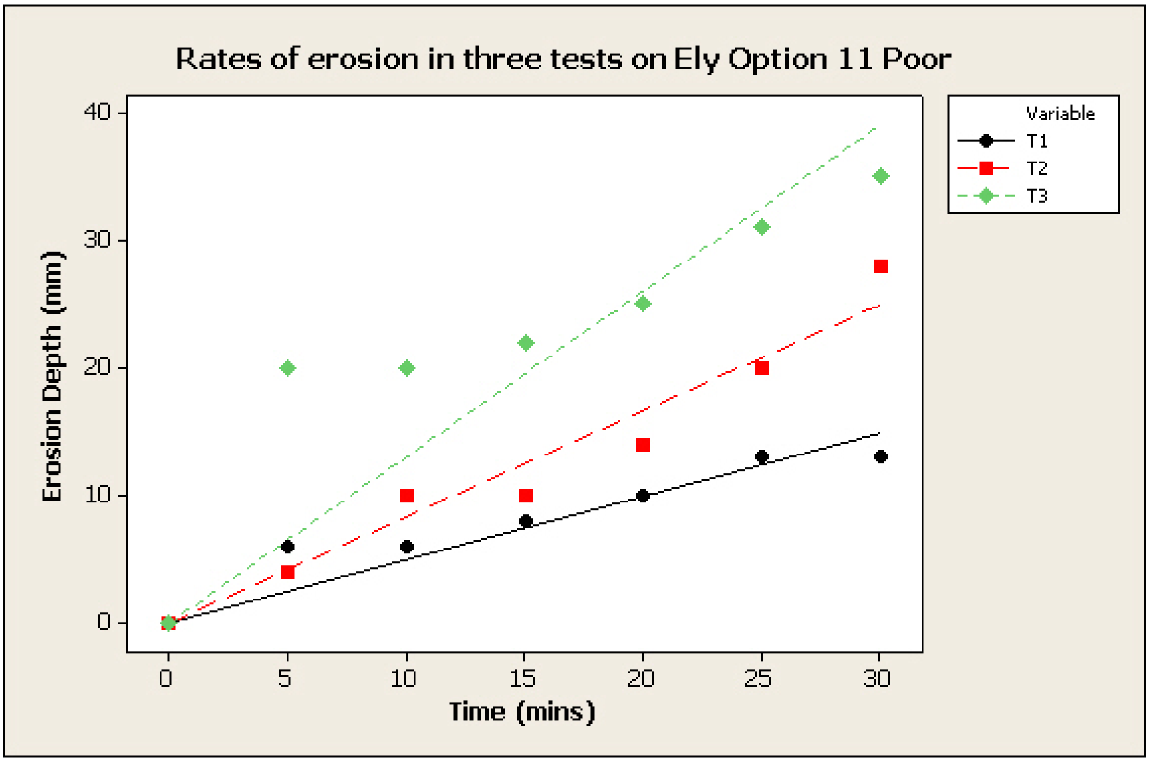

Figure 4.13 Rate of erosion of three test plots at Ely Ouse.

5 Geotechnical results

5.1 Comparison of methodologies

Although the banks would normally be cut once or twice a year, Treatment Option 11 (do nothing) is regarded here as the control treatment option.

Examining the data for the whole treatment option (i.e. not distinguishing between the ‘poor’ and ‘good’ plant cover areas), soils at Billingborough were generally significantly ($p<0.05$) weaker than at either of the other two sites across almost all treatment options (Figures 5.1–5.3).

At Ely Ouse, Treatment Options 1, 2 and 5 had significantly the strongest soils according to both the proving ring penetrometer and pocket penetrometer readings; Treatment Options 4, 9 and 11 significantly the weakest.

At Billingborough, the situation was much more confused with the proving ring penetrometer showing Treatment Options 1, 2, 5 and 9 as having the strongest soils, but with Treatment Option 9 particularly strong when assessed with the pocket penetrometer and the shear vane and significantly stronger than almost all other treatment options. Treatment Options 4 and 11 recorded the weakest soils with all instruments.

At Reach Lode, the pattern was somewhat different with Treatment Options 4 and 5 significantly the strongest and Treatment Options 1, 9 and 11 the weakest, with Treatment Options 2, 7 and 10 somewhere in between.

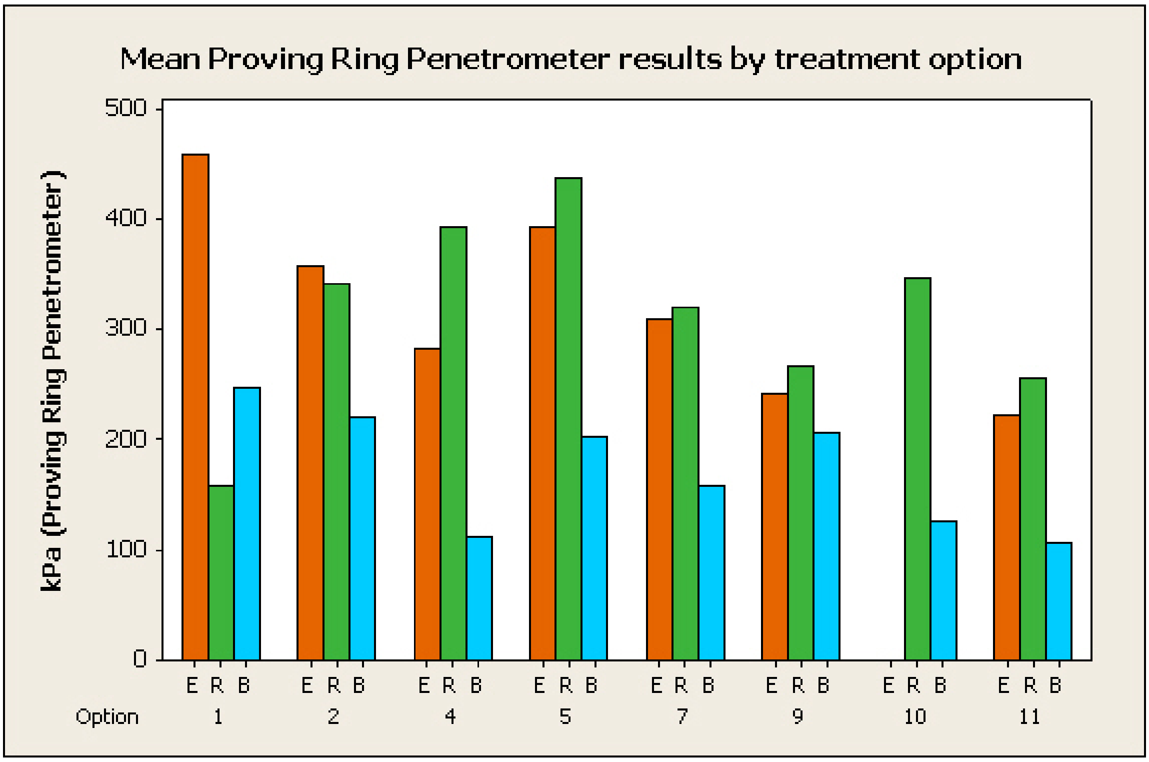

Figure 5.1 Soil strengths in the different treatment options as measured by proving ring penetrometer at the three study sites (E = Ely, R = Reach, B = Billingborough).

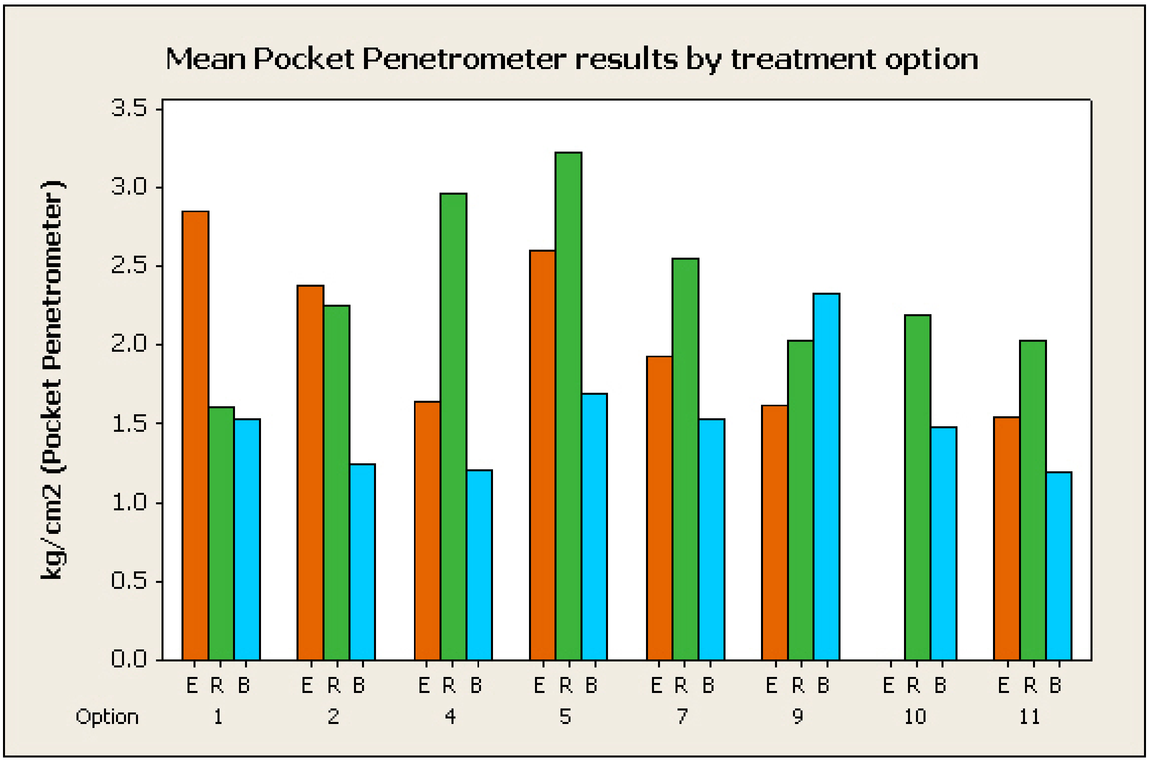

Figure 5.2 Soil strengths in the different treatment options as measured by pocket penetrometer at the three study sites (E = Ely, R = Reach, B = Billingborough).

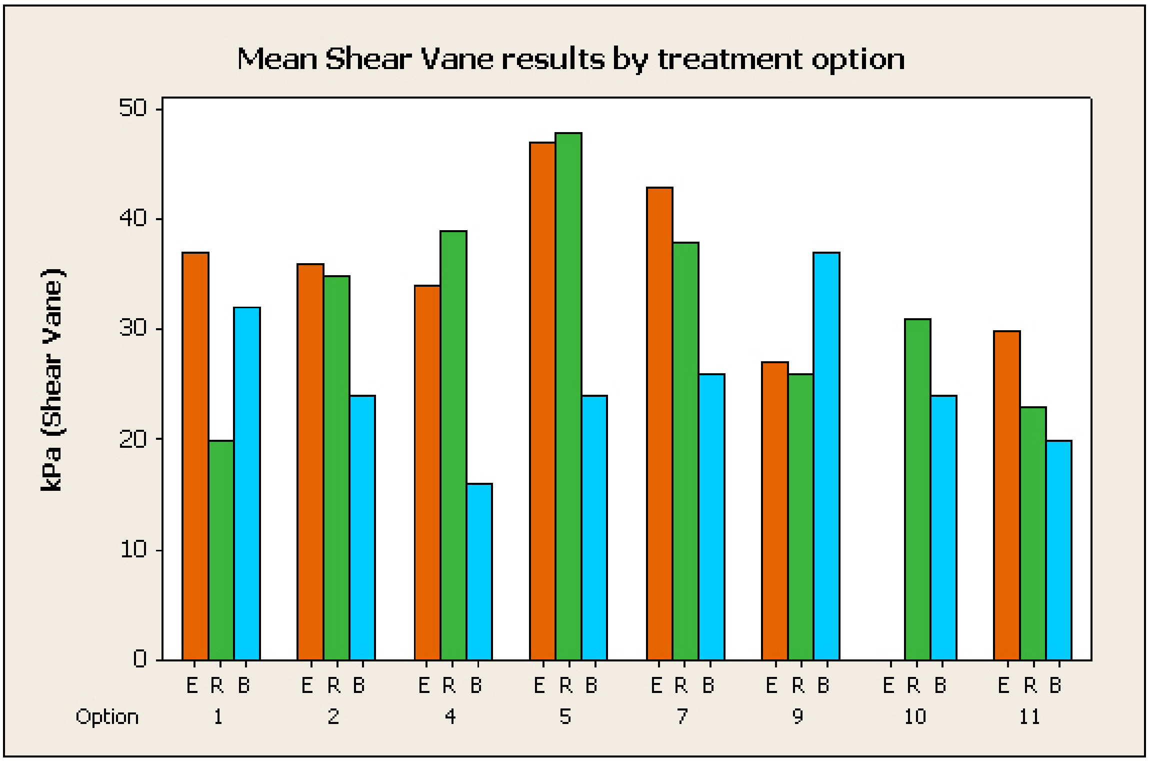

Figure 5.3 Soil strengths in the different treatment options as measured by shear vane at the three study sites (E = Ely, R = Reach, B = Billingborough).

Tables 5.1–5.3 indicate where there were significant (p<0.05) differences in soil strength between treatment options. For the purposes of these tables, the proving ring penetrometer results have been used but both the pocket penetrometer and shear vane gave similar, although not identical, results.

Table 5.1 Significant differences between treatment options[1] at Ely Ouse as assessed by the proving ring penetrometer.

	1	2	4	5	7	9	11
1		x	x		x	x	x
2	x		x		x	x	x
4	x	x		x			x
5			x		x	x	x
7	x	x		x		x	x
9	x	x		x	x		
11	x	x	x	x	x		

Notes: x = differences significant at 95 per cent confidence interval.
[1] Treatment Option 10 was not tested at Ely Ouse

Table 5.2 Significant differences between treatment options at Reach Lode as assessed by the proving ring penetrometer.

	1	2	4	5	7	9	10	11
1		x	x	x	x	x	x	x
2	x			x		x		x
4	x				x	x		x
5	x	x			x	x	x	x
7	x		x	x				x
9	x	x	x	x			x	
10	x			x		x		x
11	x	x	x	x	x		x	

Notes: x = differences significant at 95 per cent confidence interval.

Table 5.3 Significant differences between treatment options at Billingborough as assessed by the proving ring penetrometer.

	1	2	4	5	7	9	10	11
1			x		x		x	x
2			x		x		x	x
4	x	x		x	x	x		
5			x				x	x
7	x	x	x					x
9			x				x	x
10	x	x		x		x		
11	x	x		x	x	x		

Notes: x = differences significant at 95 per cent confidence interval.

5.2 Soils in good and poor areas

Looking at the three sites but considering the poor and good test areas separately tells much the same story.

At Ely Ouse, there were significant differences between the poor and good cover areas according to the proving ring penetrometer in Treatment Options 1, 9 and 11 (Figure 5.4) and in Treatment Option 11 according to the shear vane. The strongest soils were in Treatment Options 1, 2 and 5 and the weakest were in Treatment Options 4, 9 and 11. Treatment Option 10 was not tested at Ely Ouse.

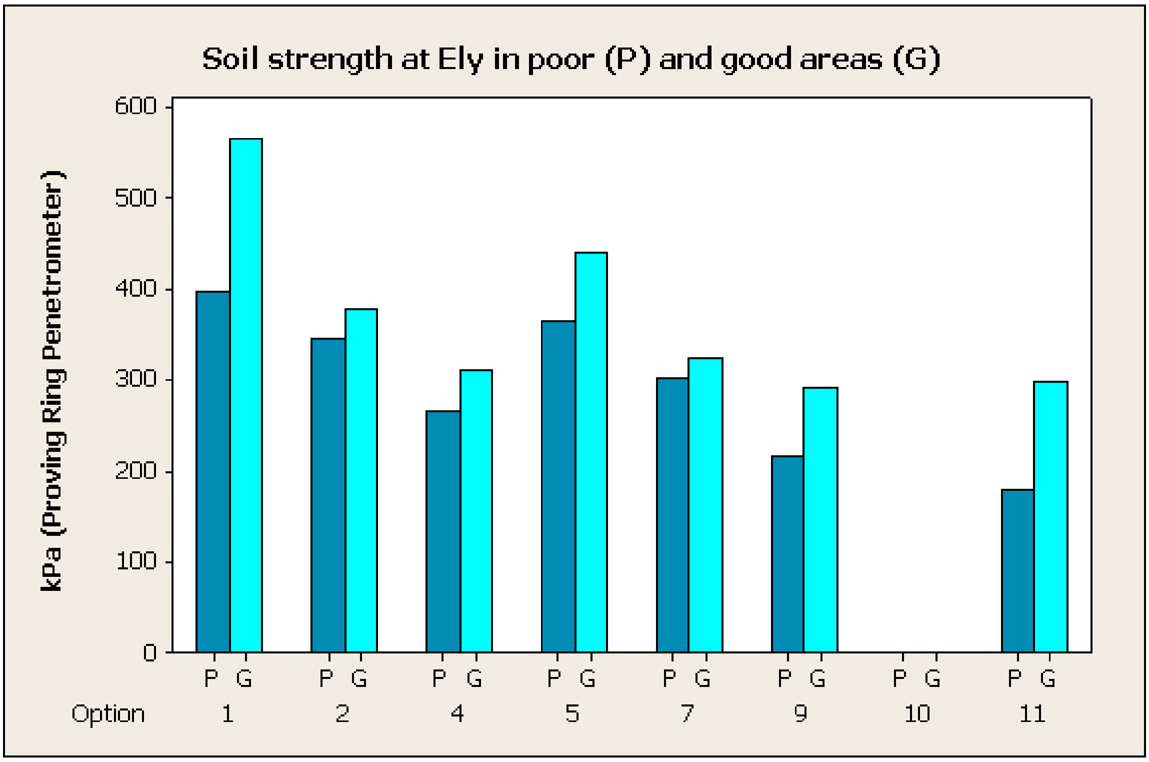

Figure 5.4 Comparison of soil strength in poor and good areas at Ely Ouse.

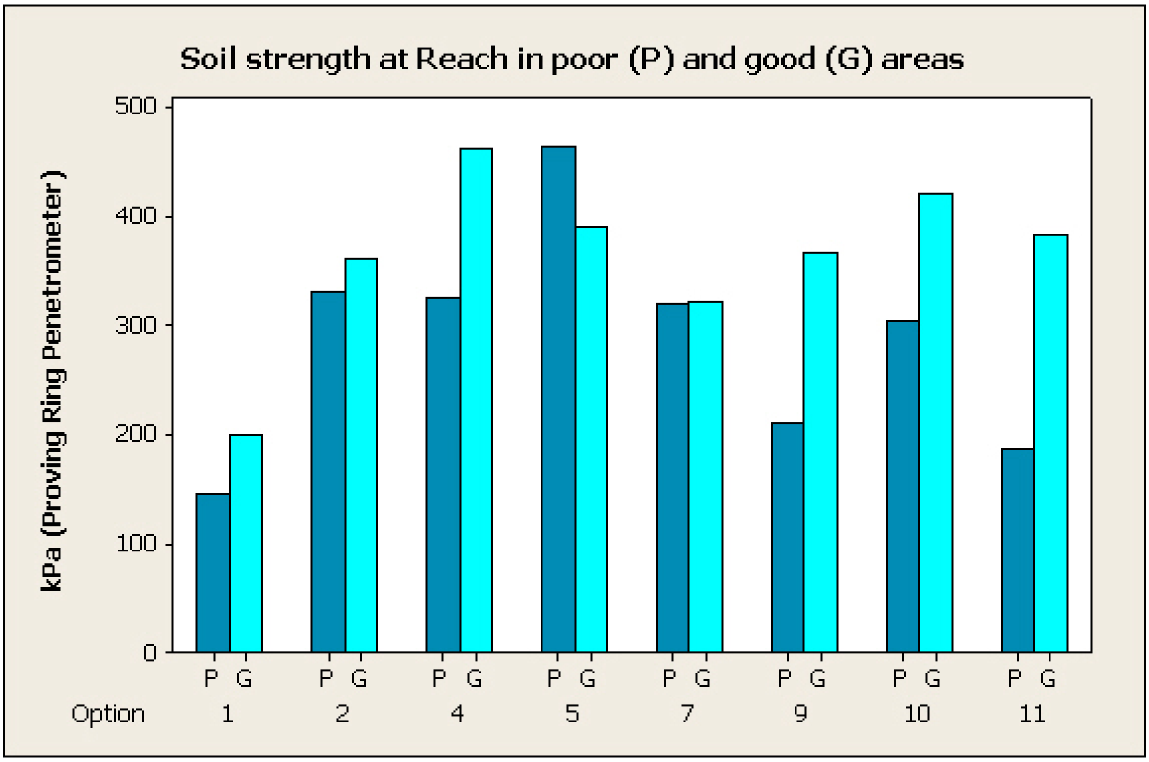

Figure 5.5 Comparison of soil strength in poor and good areas at Reach Lode.

At Reach Lode, overall strength values were of the same order as at Ely Ouse, though the differences between the treatment options were less marked. There were significant differences between the poor and good test areas in Treatment Options 4, 9, 10 and 11, but not in the others (Figure 5.5). Treatment Option 4 showed a particularly large difference here and the good areas were very strong. Figure 5.5 gives the values obtained with the proving ring penetrometer as an example but all the instruments confirm the same pattern. Treatment Option 5 was the strongest and Treatment Option 1 was particularly weak (due to the activities of moles).

At Billingborough, soils were much weaker as measured by all the instruments. Treatment Options 4 and 9 showed the only significant differences between poor and good areas, but only with the pocket penetrometer and shear vane. Rather oddly, the poor areas in Treatment Option 9 appeared stronger than the good. Figure 5.6 shows the results from the shear vane as an example. Treatment Options 4 and 11 consistently had the weakest soils, although the differences were not always significant. The position with regard to the strongest was more complicated. The proving ring penetrometer measurements suggest that Treatment Options 1, 2, 5 and 9 were the strongest, but the pocket penetrometer and shear vane indicate that Treatment Option 9 was the strongest and that there was not much to chose between Treatment Options 2, 5, 7 and 10.

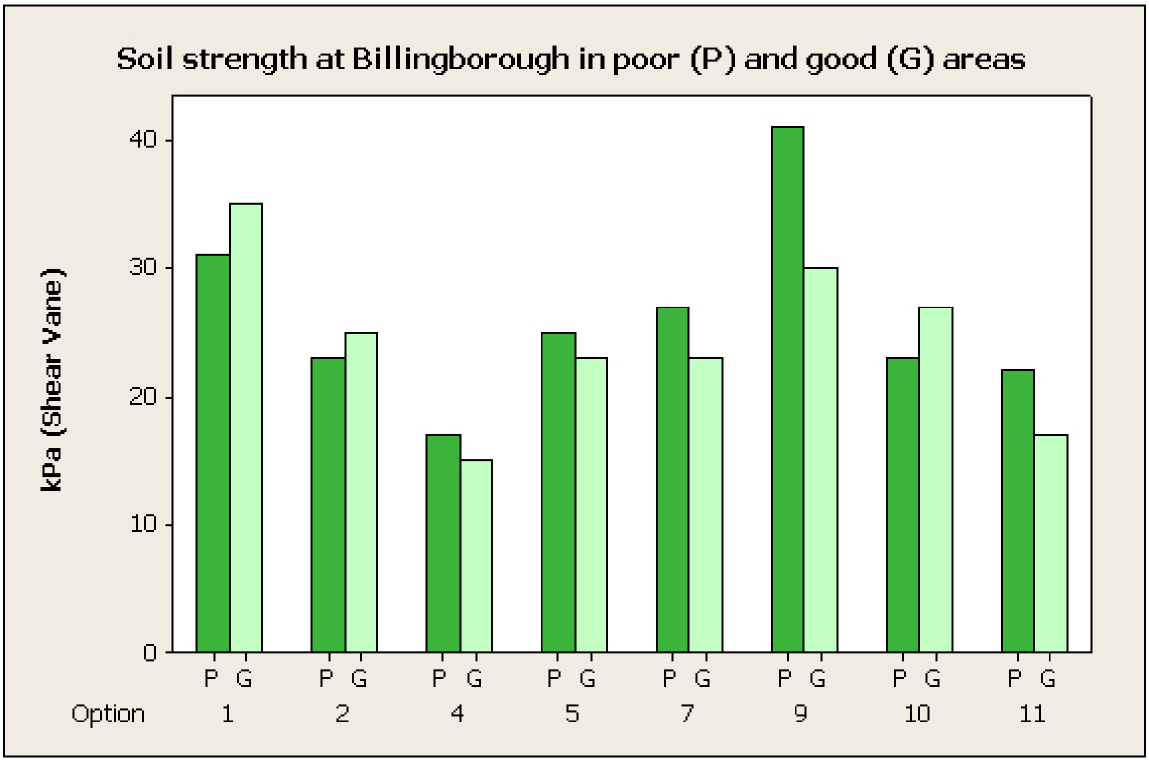

Figure 5.6 Comparison of soil strength in poor and good areas at Billingborough.

The reason for looking at soil geotechnical parameters was to see if they related in any way to the relative amounts of erosion recorded from the test areas.

- At Ely Ouse, erosion was least on Treatment Options 1, 2, 4 and 5 and most on Treatment Options 9 and 11(Figure 5.7). With the exception of Treatment Option 4, most erosion took place on the weakest plots.
- At Reach Lode erosion was least in Treatment Options 2, 4, 5, 7 and 10 (Figure 5.8). This again fits with the supposition that erosion tended to be less on the stronger soils.
- At Billingborough, Treatment Options 1, 2 and 5 showed least soil loss and 4, 10 and 11 the most (Figure 5.9). This generally fits with our hypothesis, although the strength and soil loss in Treatment Option 9 is something of an anomaly.

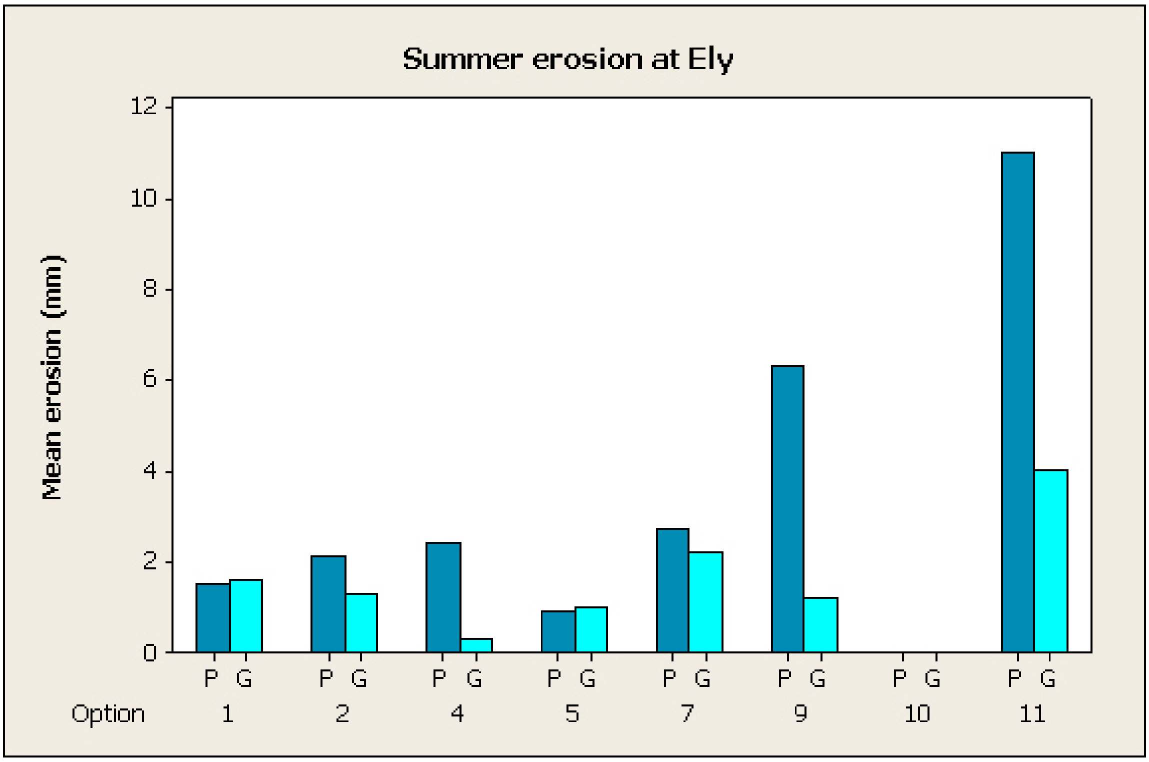

Figure 5.7 Erosion in good and poor areas in the various treatment options during the summer at Ely Ouse.

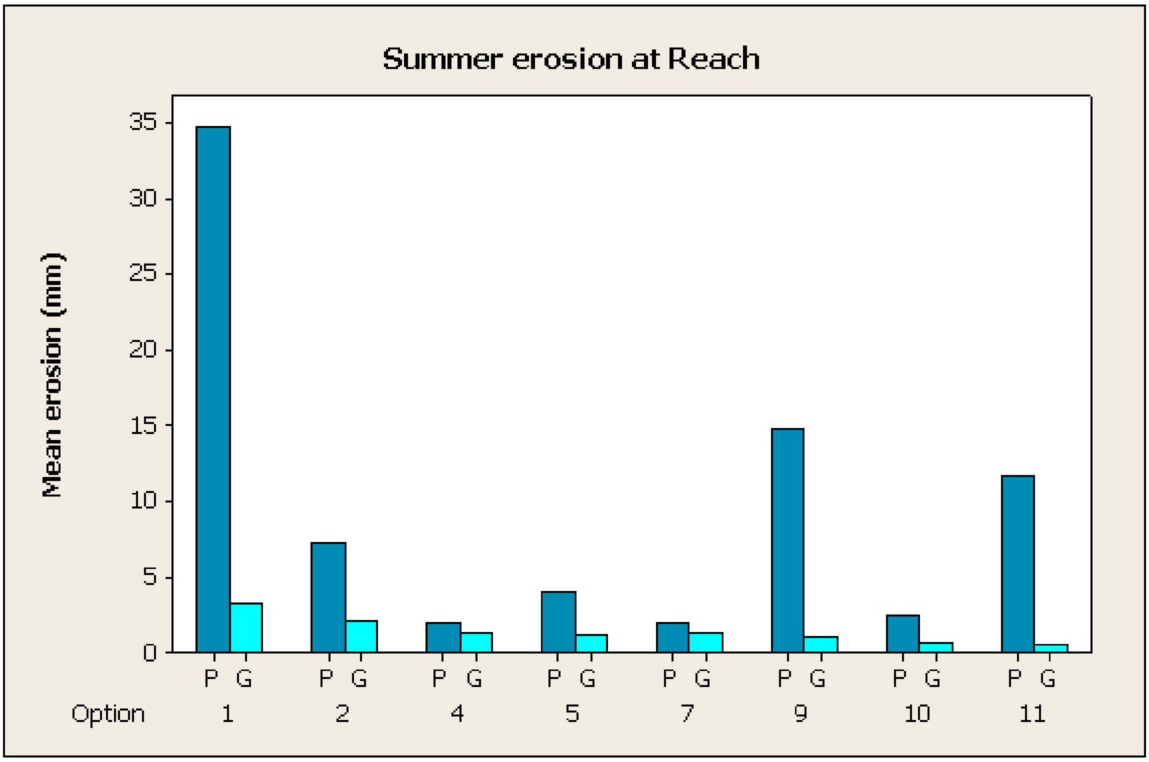

Figure 5.8 Erosion in good and poor areas in the various treatment options during the summer at Reach Lode.

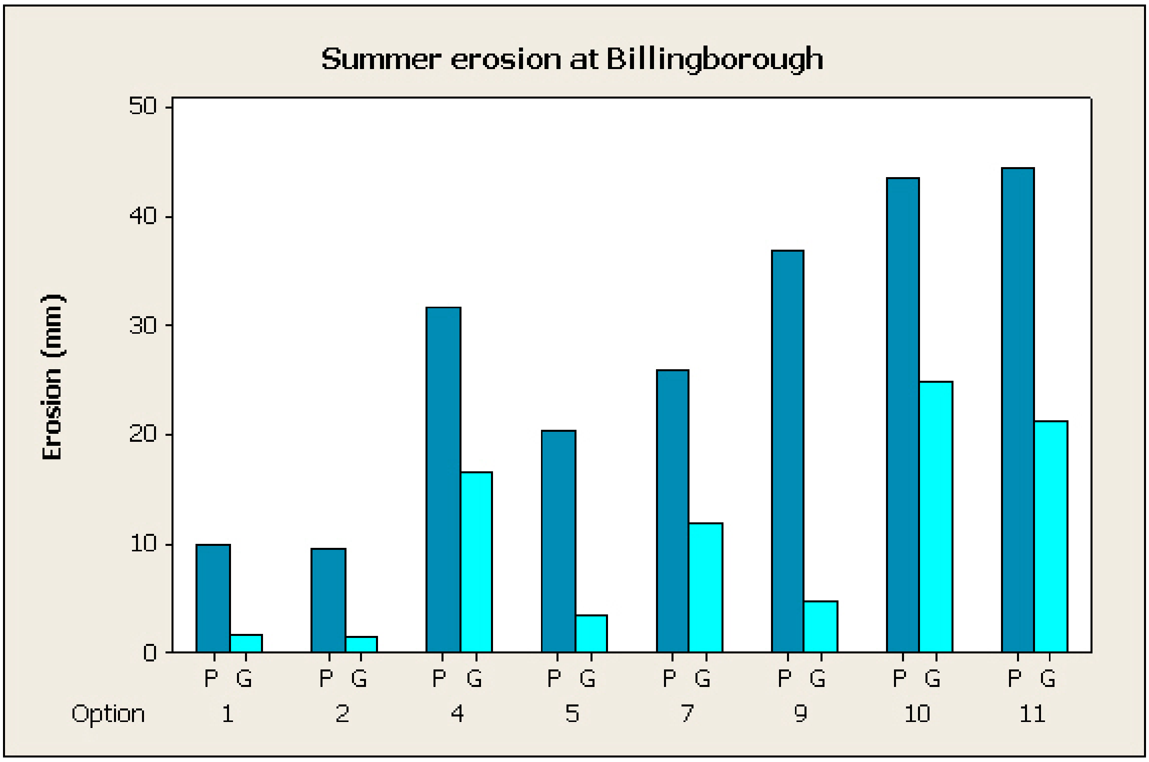

Figure 5.9 Erosion in good and poor areas in the various treatment options during the summer at Billingborough.

5.3 Seasonal changes in erosion resistance

The pre-test soil moisture results (Table 4.1) reflect differences between the sites.

Weather during the winter sampling was particularly dry and during the summer often wet. At Ely Ouse and Reach Lode, soils were 5–10 per cent drier in the summer than in winter. At Billingborough, however, there was little seasonal change and moisture contents were lower than at either of the other two sites. This probably reflects the coarser textured topsoils common on the bank at Billingborough.

Topsoils generally wetted up thoroughly during the erosion tests, although dense clay layers remained dry as did the interiors of large soil fragments washed out intact.

Data from Ely Ouse suggest that:

- replicates with the strongest soils have the smallest proportion of bare ground (Figure 5.10);
- those treatment options in which soils had the highest pre-test soil moisture contents suffered least erosion (Figures 5.11).

However, these differences are not statistically significant and were not repeated at either Reach Lode or Billingborough.

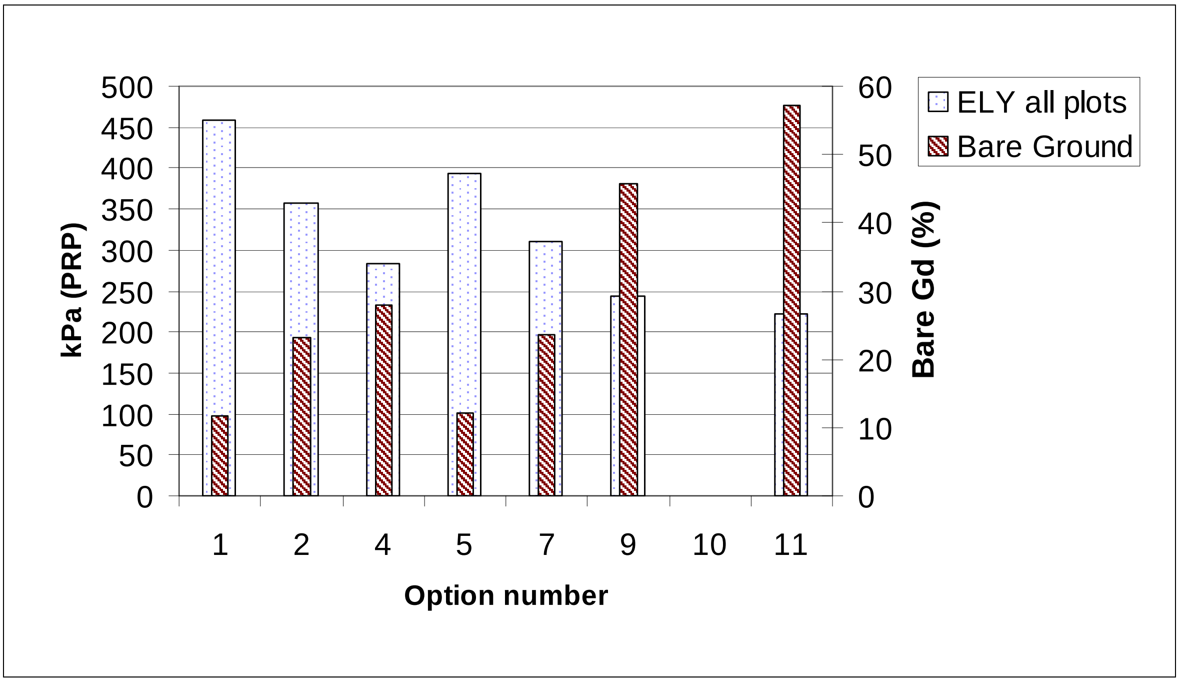

Figure 5.10 Relation between soil strength and extent of bare ground within replicate erosion plots at Ely Ouse.

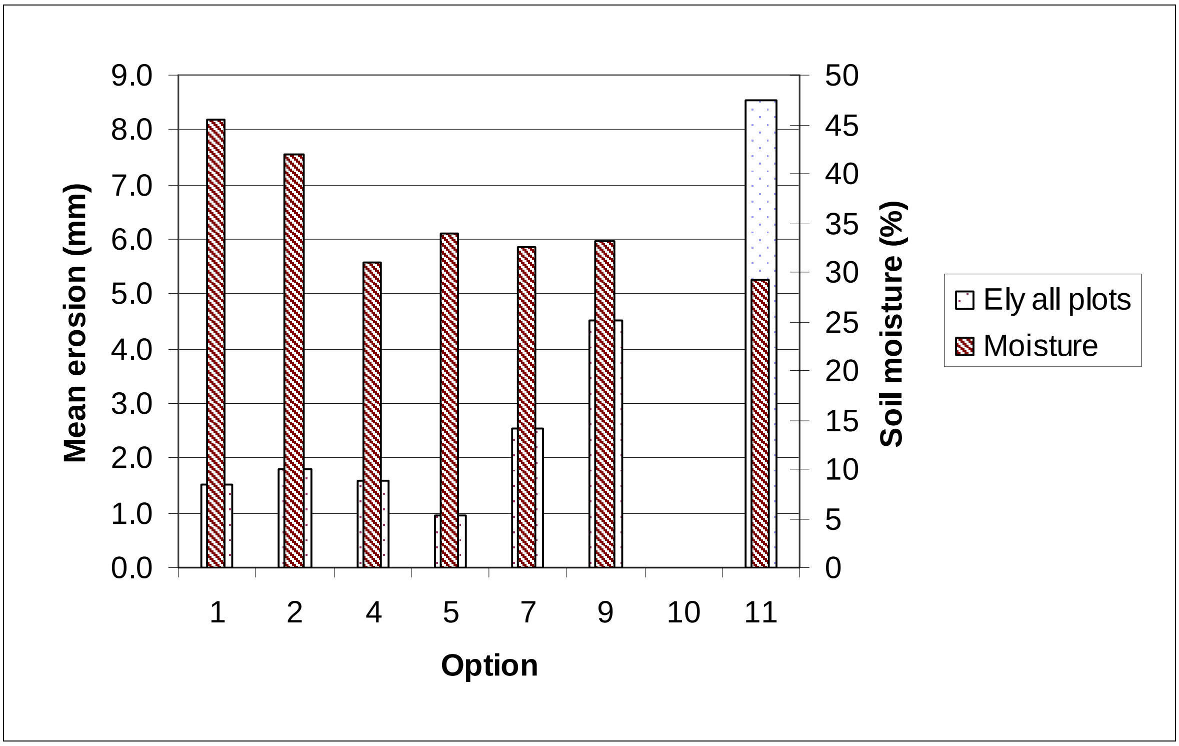

Figure 5.11 Relation between soil moisture and mean erosion at Ely Ouse.

The geotechnical tests described in this report generally found weaker soils than those recorded during the flood embankment management trials (Environment Agency 2009). This was because the former were carried out on wetted soil following the erosion test whereas the latter were performed on the soil in its natural state before the commencement of the test. But as noted previously, the soils during this test series were generally drier than might be expected. Overtopping of floodbanks is unlikely to occur in dry periods; even a short spell of rain would moisten up the surface layer of the soil where erosion would be initiated.

6 Discussion and conclusions

Experience gained during the two series of tests at the three sites suggested that the course of tests could be affected by a number of different factors. In a number of tests at Reach Lode, early erosion was halted when a coherent clay layer was reached and further erosion was extremely slow. On the other hand there were occasions when initially there was slow erosion in cohesive soils until a looser layer of soil was reached and the rate of erosion accelerated. A similar process was observed when a buried void (often in the form of an animal burrow) was reached and there was a rapid increase in the rate of erosion.

Given that the tests were run for a maximum of only 30 minutes, it is considered that only a limited degree of erosion would represent a threat to the integrity of the floodbank. The water velocity of 4 ms^{-1} used in the tests is likely to be on the low side for an overtopped bank, thus increasing the significance of even limited erosion seen in some of the tests. Further more accurate information is likely to be available soon on the probable range of water velocities likely to be experienced when a grass bank is overtopped (Utile S, personal communication).

Some of the sites and treatments showed a relatively low incidence and rates of erosion. Within each replicate, however, the vegetation and erosion test areas amounted to only 7.2 m^2 of bank. With the replication used, this amounted to 225 m^2 along 100 linear metres of bank, thus representing approximately 1 in 20 m^2.

More significantly there was generally little difficulty in locating poor areas within the replicates. As each of these might be only 0.025 m^2 (the test area of 150 $\times$ 150 mm), and although in practice the bare areas were frequently larger than this, the proportion of poor areas was considerable in all but the best parts of the most appropriate treatment options. Even if as short a section of floodbank as 10 m were to be overtopped, there is a high probability that there would be several poor areas within that section in all but the most favourable management treatment options.

The data showing the proportion of the areas assessed as 'good' which eroded and the areas assessed as 'poor' which failed to erode demonstrated the difficulties of basing any assessment of the resistance of a particular bank section to erosion if it were overtopped. The inspection of a section of bank (the 7.2 m^2 used for vegetation recording) involved a very close examination on the hands and knees – very different from the lower level of detail from just walking the bank. It is estimated that approximately one in 10 tests were probably incorrectly assessed as being good or poor.

More important is the fact that the hydraulic testing showed that, within a correct assessment, there could be very different degrees of erosion. It is not possible with the present level of knowledge to define what mean depth of erosion is likely to be critical for assessing the integrity of the floodbank, but clearly significant erosion under test does suggest that potential weaknesses are present.

The test results using the EMD indicated that the management treatment options most likely to increase the erosion resistance of the floodbank were Treatment Options 1, 2, 5 and 7, and sometimes also Treatment Option 4. Treatment Option 2 showed the best performance overall, but the differences were small and not statistically significant. While individual tests of significance may be inconclusive, similar results from different sites and also circumstantial evidence can contribute to a result that may be regarded with some degree of confidence.

During the course of the erosion tests, a number of observations were made on botanical aspects which tied in with the erosion tests in different ways.

When the grass cover consisted of the taller grasses such as *Arrhenatherum elatius*, *Elytrigia repens* or *Anisantha sterilis*, the ground coverage at ground level was limited with patches of bare ground to be found between the grass stems. It was clear that it was the proportion of ground that was covered by living vegetation at ground level that was important.

However, the presence of a good covering of grass or for that matter other vegetation did not always result in no or reduced erosion. Several times it was observed that erosion of the soil surface was occurring under the vegetation canopy, even when this was close to the soil surface.

In a few of the plots, there were stands where low growing *Festuca rubra* formed a closely interwoven cover to the soil and this appeared to be resistant to erosion.

The activities of various species of small mammals contributed significantly to the occurrence of areas of loose soil or bare ground.

Rabbit activities were generally limited to occasional scrapes along the crest of the bank and only rarely were the slopes affected to any extent.

Voles and moles were the principle cause of areas of bare ground. Only fresh molehills were avoided when bare areas were being selected, but old molehills were a major source of areas of bare or loose soil along the floodbanks at Reach Lode. Vole activity had already been noted (Environment Agency 2009) at all three sites but particularly at Billingborough.

During the erosion studies, the very distinctive hills or mounds of earth made by the water vole (Bang and Dalstrom 1972) had been noted as a frequent occurrence in the plots at Billingborough. Corbet and Southern (1977) record the main habitat of the water voles as ‘well vegetated banks of lowland rivers’ while Lawrence and Brown (1973) refer to water voles as making complicated tunnel systems in the banks with exits above and below the water. During the erosion trials at Billingborough, water was seen disappearing underground in or near the test plots only to emerge many metres away at or below river level.

The soil structure can influence the development and extent of erosion in many different ways. The structure of the soil develops as it matures. The clay, silt, sand and organic matter that are the main constituents of soil form semi-permanent aggregates (peds) which more or less fit together (Hodgson 1997). These peds are separated by voids and planes of weakness, and are formed by a number of processes acting together. Wetting and drying, root action, floral and fauna activity (macro and micro) all play their part. Peds range in size from a few millimetres up to 100 or so millimetres across.

In an agricultural context, soil structure is generally very important to crop growth – a ‘good’ structure consisting of small, well-developed peds packed fairly loosely together. This enables both rainfall and roots readily to penetrate the soil and keeps the upper layers (horizons) aerated. However, soil with such structure on the floodbanks is liable to be washed away rapidly if the bank is overtopped. A more compacted soil with coarse structure (i.e. a ‘poor’ structure in an agricultural context) is less likely to suffer erosion in these circumstances.

There is considerable variability in the soils of the embankments at the three sites but there is insufficient valid data for any firm conclusions. The embankments have each been constructed largely from what material was available locally and are particularly heterogeneous at all levels of scale. Had the embankments all been constructed from cohesive clay soils, then undoubtedly the banks would have shown a much greater resistance to erosion.

The soils on the river floodbanks are man-made. After the bank has been constructed, topsoil is laid on the surface to enable a grass cover to be sown and to become established. Although this topsoil will have some structure, its condition will depend on how long and under what conditions it has been stored and its treatment during both collection and spreading. As the grass cover becomes established, so the topsoil structure will develop with peds becoming smaller and better defined. It may take a long time for structure to develop in the subsoil as this is likely to have been compacted during construction of the embankment.

The generally more clayey topsoils at Ely Ouse and Reach Lode give rise to coarser structured, more compacted and stronger topsoils than those at Billingborough, and these differences are reflected in the erosion results.

The activities of small mammals – particularly moles and voles – can contribute significantly to the extent of bare loose soil. Bare patches can also result from the death of tall-growing ruderal vegetation which shades out the lower growing species below it. This can happen by natural processes in annual species such as *Sinapis arvensis* or it can result from the effect of cutting or herbicides on perennial species such as *Urtica dioica*. Examples of this were seen particularly at Billingborough.

However, there is another aspect to the impact of *Urtica dioica* on erosion. In a number of plots where erosion was occurring it was noted that, while the thin roots of the grass species were broken by the force of water forcing the peds apart, the rhizomes of *Urtica* maintained intact the cohesion of the larger soil particles.

In general, the test areas with the strongest soils recorded the least erosion. Taking the trials overall, Treatment Options 2 and 5 were the most consistent in having little erosion and strong soils. Treatment Option 1 was generally strong with little erosion except at Reach Lode, though this anomaly was probably due to intensive mole activity. The soil peds remain more tightly packed together and thus more resistant to erosion, under the more frequent mowing regimes. This is, at least in part, due to increased rain impact. Frequent mowing may also temporarily reduce evapotranspiration by reducing leaf area, leaving the soil moister. There is a suggestion of this at Ely Ouse and Billingborough, where the plots with the wettest soils were in Treatment Options 1, 2, and 5 and generally recorded least erosion.

A scoring system based on the average erosion recorded in summer and winter combined was devised in order to make a comparative assessment of the various treatment options at each of the three sites.

There were eight treatment options per site (seven at Ely Ouse).

The range of erosion depths at each site was divided by nine to enable ten equal classes to be constructed.

The treatment option with least erosion then fell in the middle of one class (score 10) and that with most erosion fell in the middle of the class at the other extreme (score 1). The other treatment options were then scored accordingly. The results are given in Table 6.1.

Table 6.1 Erosion scores at each of the three sites for each treatment option.

Treatment Option	Ely Ouse	Reach Lode	Billingborough
1	10	1	10
2	9	9	10
4	10	10	4
5	10	10	7
7	9	10	7
9	3	7	6
10	nt	6	4
11	1	8	1

Notes: nt = Treatment Option 10 was not tested at Ely Ouse.

However, any scoring system must be used with caution. For instance at Reach Lode, Treatment Option 1 suffered deep erosion in areas of 'poor' vegetation cover, mainly due to mole activity which has left bare areas of loose soil. Erosion here was almost twice as much as any other treatment option and so the scores of other options at Reach Lode all fall between 6 and 10. This can give the impression that these treatment options perform better than they do. If Treatment Option 1 is omitted from the process, the scores for Treatment Options 2, 7, 9, 10 and 11 become 7, 9, 3, 1 and 4 respectively.

The soil out of which an embankment is constructed will have a considerable effect, both directly and indirectly, on the erosion resistance of that bank. Banks constructed from cohesive clay soils will have the greatest structural strength and the bare surface will have a greater resistance to erosion than will non-vegetated loamy, sandy or organic-rich soils. But as these trials have shown:

- the vegetation cover of a floodbank can have a major effect on the ability of the bank to resist erosion;
- vegetation cover is greater on well-structured soils with a mix of particle sizes and appropriate levels of mineral nutrients and organic matter.

The three flood embankments in these trials all had rather mixed soils, though there was a higher clay content at Ely Ouse and Billingborough; Reach Lode soils had a generally higher organic content (Environment Agency 2009). Nevertheless the mean depth of erosion under testing at Reach Lode was rather less than twice more than at Ely Ouse, while at Billingborough it was five times that of Ely Ouse. The near absence of animal activity at Ely Ouse contributed significantly to these differences, although the detailed interactions between plants and soil clearly also play a major role.

Assessment of soil strength may thus provide a quick and partial guide to the erodibility of a floodbank. The proving ring penetrometer gave the most reliable and replicable of the three geotechnical parameters measured. The pocket penetrometer was too small in relation to the well-developed, fine and loose soil structure common in the topsoils. The shear vane performed better, but high values were sometimes more the result of roots snagging the vane than of strong soils *per se*. The proving ring penetrometer appeared best at overcoming these difficulties.

The positive correlation between the amount of erosion and bare ground in the test areas has been noted. This bare ground occurs for a number of reasons:

- faunal activity (moles and voles);
- die-back of the near surface vegetation due to shading by taller plants such as *Sinapis arvensis* by tufts of grass;

- die-back beneath dense clumps of arisings (terrestrial and aquatic) dumped on the bank.

In the bare areas caused by shading, the soil was often dry and loose, and so washed away very readily in the tests; similarly the soil was very loose in areas of faunal activity (mole and vole activity).

This research have shown that the fine, well-developed loose structure with well-defined peds, which develops under undisturbed grassland (‘good’ structure), is far from ideal on river floodbanks; peds are easily dislodged and washed out by water flowing down and across the bank during overtopping. Surface vegetation and its roots do protect from erosion to some extent, but soil is lost from within the rooting zone. Most of the erosion witnessed during this project involved the movement of peds rather than of their constituent clay, silt and sand.

It seems that, on these floodbanks, a compacted soil surface with relatively poor structure is best – at least during the initial stages of overtopping – as it gives better resistance to erosion as water flows over the surface without readily dislodging soil aggregates.

7 Recommendations

7.1 Recommendation for floodbank management

The results indicate that at least an annual cutting is necessary. Cutting at least once a year significantly contributes to bank performance, but there is little evidence that more frequent cutting is directly beneficial.

There is little evidence that removal of the arisings or more frequent cutting frequency has any great beneficial effect.

From the point of view of bank erosion, the control of small mammal activity would appear to be a significant factor. However, there are likely to be conservation issues involved – particularly in the case of voles – regarding any control measures.

The control of certain weeds can also contribute significantly to reducing the extent of bare ground. The significance of dense clumps of arisings has also been noted. In this connection, more frequent mowing (i.e. at least twice a year) and the use of cutting machinery that evenly distributes the arisings both need to be considered.

7.2 Proposals for future erosion studies

Following the completion of the erosion testing using the erosion measurement device (EMD), the following three proposals are made to exploit the opportunities offered for increasing knowledge and reducing flood risks in the area.

Each proposal is complete in itself although they are mutually beneficial. The size and scope of each proposal is dependant on the funding available.

7.2.1 Studies on interactions between water velocity and test duration

The speed of four metres per second was used in the recent trials with the EMD to ensure the optimum acquisition of data and information with the minimum of bank damage. The value of this information could be increased by some trials on the inter-relationships between time of test and water velocity with the depth of erosion.

In an actual flood situation, the velocity of the water flow would depend on the depth of overtopping so tests of the effect of a range of velocities would be of considerable value.

Studies are already in progress on the relation between the depth of overtopping and the resultant water velocities down the back of the floodbank, so studies on the relationship between water velocity and depth of erosion are the key to further progress regarding the prediction of erodibility.

Given the comparatively short period of the test in these trials (0.5 hours), the acquisition of data relating to the duration of testing with the depth of erosion is also of critical value.

7.2.2 Different grass varieties and their relative resistance to erosion

The recent erosion trials showed the detailed structure of the plant cover to be crucial in the depth of erosion when the bank is exposed to fast water flow. The significant reduction in erosion when the vegetation cover included dense growth of fine leaved grassed was noted.

Many different grasses are commercially available, but the properties normally tested relate largely to their appearance and wear resistance (BSPB/STRI 2007). The EMD could be very effectively used to test the erosion resistance of different grass species and varieties. This could be carried out using small plots (about 2–3 metres long) set up on a length(s) of non-critical floodbank. The plots would be sown using a range of the latest grass varieties whose properties are most likely to favour high erosion resistance. After the swards had developed sufficiently, they would be tested with the EMD.

The grass varieties showing the best resistance to erosion could then be included:

- in seed mixtures used for new floodbanks;
- in the course of repair work to weak or damaged banks;
- for direct drilling into the grass swards on existing banks with inadequate vegetation cover.

7.2.3 Testing major floodbanks for their resistance to erosion

The trials showed how the EMD can make a much more efficient and more reliable assessment of the condition of floodbanks than the current visual inspection methods.

Floodbanks identified as protecting key assets and infrastructure could be subjected to systematic testing procedure and any weak sections reliably identified. Remedial measures could then be applied judiciously, thus significantly reducing the possibility of bank failure and the consequential major incidents and extra expenditure.

7.2.4 Investigating the optimum time of year for the application of selected management regimes on floodbanks

The recently completed flood embankment management trials (Environment Agency 2009) have indicated criteria for the selection of appropriate regimes for the management of the vegetation on flood embankments. These trials considered only the application of the regimes under test at set time(s) of the year. It is proposed that trials should be conducted to investigate the effects of cutting at different times of the year on the erosion resistance of the resultant vegetation. Cutting frequencies of one or two times per year have economic benefits over more frequent cuts. The benefits of regimes with low cutting frequencies may be enhanced by determining the optimum time of year for the application of the management option.

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List of abbreviations

ELP	Ecology, Land, and People [consultants]
EMD	erosion measurement device
kPa	kilopascal
ms^{-1}	metres per second
PRP	proving ring penetrometer
PP	pocket penetrometer
SV	shear vane

Glossary

Aggregates	These are lumps or clods of soil consisting of clay, silt and sand particles, and organic matter bound together. Aggregates include naturally occurring peds and man-made lumps and clods formed by cultivation, excavation and similar activities.
Arisings	The cut grass and other vegetation left on the surface of the ground after the application of mowing in the course of vegetation management.
Erodibility	The extent to which an object (e.g. the grass-covered soil) resists erosion by, in this case, running water. In these studies, erodibility has been defined by the mean depth of erosion that occurs after applying a set water velocity for a standard time.
Erosion	The processes whereby the soil surface is lowered by the removal of soil particles from the surface by running water or other processes. Conversely erosion is reduced when the particles are held together by natural cohesion of the soil or by plant roots holding the soil peds together.
Erosion recording plots	Within each set of three vegetation recording plots, there were 14 erosion recording plots.
Geotechnical	Relating to soil strength from a civil engineering perspective.
Good areas	Areas of the replicate plots which have a complete or near complete vegetation cover (cf ‘poor areas’).
Treatment Option	The experimental area that has been subjected to a specific management routine (e.g. mowing three times a year with removal of arisings). Within each treatment option, there were three vegetation recording plots.
Peds	These are naturally occurring aggregates of clay, silt and sand particles, and organic matter – the main constituents of soil. Peds are semi-permanent; they are separated by voids and planes of weakness, and are formed by a number of processes acting together such as wetting and drying, root action, and floral and fauna activity. Peds range in size from a few millimetres up to 100 or so millimetres across.
Parameters	A measurable or quantifiable character or property of a situation or a process.
Penetrometer	A device for measuring the resistance of soil to the penetration of the surface. It has a cone (proving ring penetrometer) or cylindrical probe (pocket penetrometer), which is pushed into the soil to a set depth. The force necessary is recorded, and the strength or resistance to penetration of the soil calculated from this and the shape and dimensions of the probe.

Poor areas	Areas with of the replicate plots that have a reduced vegetation cover and noticeable areas of bare ground (cf 'good areas')
Shear vane	This measures the shear strength of soil. Blades of known dimensions are pushed into the soil and the force needed to turn these blades (so shearing the soil) is recorded. From this force and the dimensions of the blades, a shear strength is calculated.
Vegetation recording plots	Within each treatment option, there were three separate areas used to monitor changes in the vegetation during the five years of the trials.
Weed wipe	A spongy material impregnated with systemic herbicide (weed killer) used to kill tall-growing weeds by wiping the leaves.

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