Limiting sediment deposition on roadways: topographic controls on vulnerable roads and cost analysis of planting grass buffer strips

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Abstract

Effective erosion control requires both a sound understanding of the physical context and sufficient motivation on the part of farmers to act, and in Europe this almost inevitably depends on financial subsidies. In south-west France, intense spring and summer storms lead to large scale sediment deposition on roadways, and cleanup costs are a major concern for local authorities. Current erosion control subsidy rates are not sufficient to encourage farmers to limit erosion and reduce cleanup costs. The objective of this study was to define the topographic characteristics which control sediment deposition on roadways in order to compare the cost of planting grass strips along these roads to current cleanup costs. Topographic conditions were characterised by midslope inclination (with a range of from 6 to 8%) and distance of this slope to the road (range of 50–200 m), and these were defined by a combination of field visits, air photos, and GIS techniques. The effect of grass buffer strips on sediment deposition was estimated using the revised universal soil loss equation (RUSLE). The financial benefits of planting grass strips were based on the estimated efficiency of the buffer strips and the length of roads affected according to the topographic conditions. More than 70% of roads requiring regular cleanup occur within 200 m of a midlsope inclination of 6%. Errors in predicting sediment deposition sites according to topography occur mainly when small scale changes in topography are beneath the resolution of the Digital Elevation Model (DEM) or when sediment deposition occurs due to the intersection of talwegs with roads. Modelling the effects of grass strips on soil erosion rates suggests that buffer strips of 12 or 24 m wide reduce sediments leaving the field by 32 and 54%, respectively. Planting grass buffer strips along predicted problem road sections can reduce cleanup costs associated with sediment deposition. Savings in the first year of planting are in the order of about 2% of current estimated cleanup costs (100,000) for 12 m wide strips, and this amount increases to almost 35% in subsequent years for 24 m strips. Savings in cleanup costs can be used to increase erosion control subsidies, thereby ensuring a higher level of farmer participation. In addition to reducing sediment deposition on roadways, the grass buffer strips serve as demonstration plots for the farming community. The strategy does not directly eliminate soil degradation upslope, but it is a first step towards better erosion control.

1. Introduction

The physical processes of soil erosion have been the sub- ject of intense investigation for at least half a century, but strategies to fight erosion have met with only limited success. One reason for this is that the socio-economic factors that drive erosion are rarely taken into consideration in erosion studies, so conservation planning techniques lack signifi- cance for the farmer who decides on landuse practise. Soil erosion of agricultural land in SW France has several reper- cussions. The main on-site consequence is long-term loss in soil productivity. Off-site, deposited sediments in

ditches and roadways incur important costs for local public agencies. Although lost soil productivity is the greater environmental threat in the long term, it goes mostly unnoticed because of more productive crop varieties and greater fertiliser ap- plications. Since soil degradation is not yet perceived as an important issue by farmers, soil erosion control incentives in the region have been a failure. Moreover, erosion control subsidies do not fully compensate losses in crop yields asso- ciated with measures such as grass strips or vegetated fallow. Farmers respond more to short-term financial incentives than to long-term environmental considerations (Boardman et al., 2003), so it is essential that subsidies equal per hectare revenues for farmers to adopt erosion control strategies.

Although the loss in revenues associated with soil degra- dation (lower yields) from erosion go largely unnoticed, short-term costs associated with road cleanups, on the other40   *J. Morschel et al./Environmental Science & Policy 7 (2004) 39–45*

hand, attract attention because they generate immediate quantifiable costs. A similar situation was observed in Bel- gium where off-site problems focussed attention on erosion long before the risks associated with on-site degradation (Verstraeten et al., 2003). In addition, sediment deposition on roadways represents an inconvenience for commuters since roads need to be closed until cleanup operations are ended.

A short-term erosion control approach might achieve more success if efforts were concentrated on fields that repeatedly lead to large scale sediment deposition on roadways. The objective of this study is two-fold: to identify topographic controls on road deposits, and to compare the costs of ap- plying soil erosion control measures at these sites to current cleanup costs. The use of models is an important addition to field observations in soil conservation planning (Verstraeten et al., 2003), and the revised universal soil loss equation (RUSLE) (Renard et al., 1997) was used to model the ef- fectiveness of grass strips in order to calculate the costs of implementing erosion control strategies.

2. Study area description

2.1. Environmental context

The "Lauragais" region, where the study was conducted, is located within a larger area of crop land, the "coˆteaux du Sud-Ouest," near Toulouse in south-west France. It is one of France's main agricultural regions despite a hilly topography: 58% of slopes have inclinations less than 5%; 33% have inclinations greater than 5% and less than 10%; and 9% have inclinations greater than 10%. Slopes up to 35% are cultivated. Most slopes have a convexo-concave profile, where relatively straight segments are found between the upper convexity and lower concavity and between the lower concavity and downslope field limit. A single field generally extends from the crest down to a road or stream.

Several crop types are grown, including wheat, corn, soya beans, canola, and sunflower, but the most common crop ro- tation is winter wheat–sunflower. Erosion rarely occurs on wheat fields, which are well in place before spring and sum- mer storms, but the soil is bare every second year preceding planting and growth of the sunflower crop. Towards early July, sunflower plants are sufficiently developed to protect the soil against raindrop impact and surface runoff. There- fore, the vulnerable erosion period extends from early April to early July. About 90% of roadway sediment deposits oc- cur during this period with 52 and 38% in the spring and summer, respectively (Ministère de l'Environnement, 2000). Rainfall intensities for 2-year return periods are 71.0 and 59.2 mm h^{-1} for   durations   of   6   and   15 min,   respectively   (Météo France, 2000).

Soils are formed on a calcareous substrate and belong to either calcic cambisols or calcic luvisols in the FAO taxon- omy (Revel and Guiresse, 1995). Soil analyses show that
typical soil textures range between 25 and 35% clay, 30 and 40% silt, and 30 and 40% sand. Aggregate stability mea- surements (Le Bissonnais, 1996) indicate that soil aggregate stability is good, and the soils are not particularly sensi- tive to surface crusting. The soil, therefore, has a relatively low inherent erodibility, but the combination of topographic and climatic factors has created erosive conditions. Water erosion is widespread, and on convex crests tillage erosion has contributed to strip the soil cover (Guiresse and Revel, 1995), so yields of sunflower and sorghum are about 20 and 30% lower, respectively, in these areas (C.A.H.G., 1994). Tillage erosion redistributes soil within the field but does not contribute to sediment deposition on roadways.

Erosion has accelerated since the 1970s due to an increase in field size. Aerial photographs of the study area show that average field size grew from 3.5 ha in 1948 to 13.4 ha in 1972 and 25.4 ha in 1998. Fields, previously divided into differ- ent crop types, are now bare from crest to roadway; runoff velocity increases on longer slopes, as does the potential for creating zones of runoff concentration and rill erosion. In addition, natural barriers to runoff, such as hedges and wooded slopes, have been suppressed. Under certain topo- graphic conditions, some fields generate sediment deposits on roadways. The first objective of this study is to define these topographic conditions in order to better identify and map critical areas for erosion control measures and to define slope profiles to be used in simulating the effects of grass strips.

2.2. Erosion control and road cleanups

Soil erosion measures are effective only if farmers are convinced they will require little investment in either time or money. Efficient use of public funds must therefore take into account the motivational impact on farmers and the pub- lic benefits gained from erosion control measures. One ap- proach is to weigh the cost of current road cleanups against erosion control measures in high risk zones. Currently, sub- sidies for erosion control measures are available to farm- ers, and the primary objective is to protect waterways from sediment/pesticide/fertilizer inputs. This approach, however, has failed for the reasons described above (insufficient mo- tivation due to low funding and the perception of farmers that erosion was not a critical problem) and noted else- where (Verstraeten et al., 2003). An alternative initial strat- egy would be to focus on critical road sections: one benefit of this would be to provide demonstration plots necessary to convince farmers of the efficiency of soil conservation prac- tises (Verstraeten et al., 2003). It must be recognized that this does not address the crucial issue of soil degradation upslope, but it does initiate soil conservation practises that could later be expanded once farmer acceptance is gained.

The "coˆteaux du Sud-Ouest" region is divided into dif- ferent administrative sectors, each with its own technical crew (Direction Départementale de l'Equipement, DDE) responsible for road maintenance. Formal records are not kept concerning cleanups, so it is difficult to associate particular rainfall events with deposition occurrences. In addition, some road sections require interventions two or three times per year while others only once every couple of years. Defining the topographical characteristics of vul- nerable road sections facilitates both the mapping of these zones and an estimate of costs associated with applying erosion control measures to these sections.

3. Defining vulnerable road sections

Defining topographical characteristics and mapping high risk road sections was carried out in three steps: initial sur- vey, definition of topographic conditions, and evaluation of the chosen conditions to represent sensitive road segments.

3.1. Initial survey

Highly sensitive road sections were identified with offi- cials from the Villefranche de Lauragais office of the DDE. The sector covers an area of about 190 km2. Approximately 21 km of roadway were identified as requiring regular inter- vention, though frequency of intervention was impossible to determine since precise records were not kept. Field visits were made to each of the sites to get an initial estimate of topographic features which could contribute to sediment de- position: these included slope inclination, distance between steep slope section and roadway, and the presence of lo- cal depressions or zones of flow concentration. These visits were complemented by analyses of aerial photographs for the entire sector.

The initial survey suggested that two types of topographic controls influence sediment deposition: (1) flow is concen- trated along slopes toward a thalweg, or (2) sensitive lin- ear road sections are found along areas with steep slopes in proximity of the roadway. In the first case, sediment de- position occurs over a limited road length distance which corresponds to the intersection between roadway and thal- weg. This situation accounts for only a small percentage (fewer than 10%) of high risk road sections due to a general NW–SE crest/valley alignment of convexo-concave slopes throughout the landscape. Major roads tend to follow the crests or valleys, with valleys being affected in the valley bottoms. The second type generates longer deposition zones (up to about 1 km) along roadways parallel to slope crests. For this second type, two topographic controls had to be defined: minimum critical midslope inclination and critical midslope inclination distance from the roadway.

Before going further, it is worth noting that the two to- pographic conditions, minimum critical slope and distance from the road, account for different physical processes. Minimum critical slope refers to the inclination of the mid- slope section where rill development is most extensive. Upslope sections, degraded more particularly by tillage ero- sion, have lower infiltration rates than downslope sections due to a combination of thinner soils and lower clay and organic matter contents (Bruno and Fox, 2003), so they generate high runoff rates. Rills develop mainly in tractor wheel depressions on midslope segments, and they fre- quently attain widths of about 20 cm and depths of 10 cm. Midslope sections generate most of the sediments deposited on roadways, and the minimum critical slope angle referred to applies to this section. The importance of slope angle for erosion processes is well known (Renard et al., 1994; Fox and Bryan, 1999) and requires no further explanation. Slope length is a secondary topographic control increasing erosion (Renard et al., 1994), but our initial survey indicated that it shows no systematic relationship with sensitive road sections. However, in other areas this may not be the case.

The downslope section serves as the main deposition area for sediments eroded on the midslope. The second parame- ter, distance between minimum critical slope and roadway, refers to the length of this lower slope section. Combining downslope section inclination with distance would proba- bly have improved the model since slope influences flow velocity (Fox and Bryan, 1999) and hence deposition rate. However, the Digital Elevation Model (DEM) does not de- tect subtle changes in slope required for deposition mod- elling. Furthermore, downslope sections have been the site of sediment

accumulation over several decades (Revel and Guiresse, 1995), and they generally slope uniformly toward the ditch/roadway at an angle of about 2–3%. Distance from the roadway therefore represents a measure of the likeli- hood of sediment deposition within the field and not an erosion-increasing factor as it would on the midslope sec- tion. As distance increases, deposition within the field be- comes more likely.

3.2. Defining the topographic conditions

After the initial field and air photo surveys, several com- binations of minimum critical slope inclination and distance from the roadway were tested. These included all combina- tions of lower slope limits of 6, 7, 8, 9 and 10% and slope distances of 50, 75, 100, 125, 150, 175 and 200 m (35 possi- bilities in all). The combination of lowest slope and greatest distance represents the least restrictive conditions, and that of steepest slope and shortest distance the most restrictive.

Model elaboration was carried out using GIS software. Layers used were the following: (1) a Digital Elevation Model (DEM) at a 50 m grid, (2) roadways digitised from 1:25,000 topographic maps, (3) thalwegs and river sections derived from the DEM and complimented by the addition of the historic "Canal de Midi," and (4) forested zones, ob- tained from 1998 aerial photographs (there is virtually no permanent grass and practically all of the area is used for crops, forests accounting for less than 5% of the surface cover).

The database was then queried to identify all road sections at the base of slopes corresponding to each of the combina- tions identified above: for example, all road sections within 200 m of a slope greater or equal to 6%. Query results were then compared with actual road sections identified with the help of the DDE. The comparison revealed that three road section types were generated: sections with a history of cleanups predicted accurately by the slope–length combina- tion, road sections with cleanups not identified, road sections predicted as vulnerable sites but with no record of cleanups. These sections will be considered individually in the results.

4. Results and discussion

4.1. Slope–length combination results

The distribution of road lengths according to type for all combinations are presented in Table 1. Values for total road length range from 5.9 km for the most restrictive conditions (10%, 50 m) to 46.4 km for the least restrictive (6%, 200 m). As slope diminishes (less restrictive) and as distance in- creases (less restrictive), total roadway length predicted by Table 1 Road lengths (km) for each combination of minimum midslope inclination (%) and distance (m) of this slope from road section the slope–length combination increases. The actual value of about 22.7 km lies between the two extremes of 5.9 and 46.4 km, suggesting that the most restrictive conditions gen- erate too few road segments and the least restrictive too many. Planting grass strips along the entire length would therefore generate unnecessary costs since long segments of low risk roads would be treated along with the actual prob- lem sections. It is therefore necessary to select slope–length conditions which optimise the grass strip locations.

Three trends can be noted in Table 1. Firstly, the length of correctly predicted road segments increases with total road- way length predicted: values range from 2.3 to 16.2 km for the two extreme combinations cited above. Secondly, the length of unpredicted road sections diminishes as the length of correctly (or total) predicted ones increases. Thirdly, as the length of total predicted road sections increases, so does the length of falsely predicted road segments (roads with no his- tory of cleanups). Hence, using less

restrictive topographic conditions correctly predicts a larger proportion of real high risk sites, but it also classifies as high risk more road seg- ments with no history of cleanups. The ideal slope–length combination should therefore maximise correct prediction of high risk road sections and minimise both unpredicted and falsely predicted road lengths. The selection of suitable slope–length combinations for erosion control from the list in Table 1 was carried out in two steps. In the first, it was arbitrarily decided that the combination should accurately identify at least half (11.3 km) the actual high risk roads. In the second, the selection was based on predicted cleanup cost savings associated with each of the retained combinations.

Table 1
Road lengths (km) for each combination of minimum midslope inclination (%) and distance (m) of this slope from road section

Slope–length combination	Total road length	Correct road length	False road length	Unpredicted road length
6–50	9.7	3.2	6.5	19.5
6–75	24.8	7.4	17.5	15.3
6–100	29.5	9.5	20.0	13.2
6–125	34.5	11.3	23.2	11.4
6–150	39.6	13.5	26.1	9.2
6–175	41.7	14.6	27.1	8.1
6–200	46.5	16.2	30.2	6.4
7–50	7.8	2.4	5.4	20.3
7–75	19.7	6.0	13.7	16.7
7–100	23.8	7.1	16.7	15.5
7–125	29.1	9.1	20.0	13.6
7–150	34.3	11.5	22.8	11.2
7–175	37.3	12.5	24.8	10.1
7–200	42.7	14.9	27.8	7.7
8–50	12.1	3.4	8.7	19.3
8–75	14.4	4.2	10.2	18.5
8–100	18.3	5.8	12.5	16.8
8–125	21.9	7.2	14.7	15.4
8–150	26.8	9.4	17.3	13.2
8–175	29.5	10.2	19.3	12.5
8–200	35.6	13.0	22.7	9.7
9–50	9.8	3.0	6.8	19.7
9–75	11.8	3.8	8.0	18.9
9–100	14.1	4.9	9.2	17.8
9–125	17.3	6.4	10.9	16.3
9–150	21.2	8.2	12.9	14.4
9–175	23.1	8.8	14.3	13.9
9–200	28.3	10.7	17.6	12.0
10–50	5.9	2.3	3.6	20.4
10–75	8.1	3.3	4.8	19.4
10–100	10.3	4.2	6.0	18.4
10–125	12.3	5.5	6.8	17.2
10–150	15.6	7.2	8.3	15.4
10–175	17.5	8.0	9.5	14.7
10–200	21.5	9.5	12.0	13.2

As mentioned above, the length of falsely predicted ero- sion sites increases with the length of correctly predicted sites since less restrictive conditions (lower slope–greater length) include longer segments of road. Grass strips would only diminish the costs of road cleanups on the high risk road sections; unpredicted erosion sites represent a loss in potential savings since these real high risk roads would go untreated, and falsely predicted sites would generate unnec- essary expenses since their treatment would not result in a reduction in the cost of road cleanups. The two problematic situations in our analysis (unpredicted and falsely predicted sites) will be looked at in more detail before proceeding to an estimate of the actual savings from using the method to predict grass strip location from topographic conditions.

4.2. Evaluation of the unpredicted and falsely predicted erosion sites

Two types of roadway sections need to be looked at in more detail: these are the unpredicted erosion sites and the falsely predicted sections. Three reasons can account for unpredicted erosion sites. Firstly, some road sections oc- cur in topographic depressions that correspond to thalwegs intersecting with roadways as described above. Slopes in proximity are less than the critical slope selected, but the concentration of flow in the micro-catchment is sufficient to Slope–length combination entrain sediments onto the roadway. Secondly, local small scale changes in downslope inclination may significantly alter flow direction, and these would not be accounted for by the slope–length combination. Thirdly, limits of cleanup sections could not always be defined exactly, and since many of the unpredicted sites are next to correctly predicted zones, these may result from either small scale topographic controls or incorrectly defined road cleanup boundaries.

Many falsely predicted sections are found along tributaries of the main NW–SE drainage basin. In these sections, large amounts of sediments from adjoining fields probably enter ditches, but the slope of the ditch is sufficiently great to enable the runoff to carry sediments down to the waterway or to high risk road sections nearer the main channel. This appears to be the case for at least two of the unpredicted sites: they occur where a northward flowing ditch crosses the main NW–SE road.

4.3. Economic considerations

As noted by Verstraeten et al. (2003), the "implemen- tation of certain (soil conservation) practises is highly dependent on whether or not subsidies are involved." For the purposes of the study, the DDE estimates cleanup costs at about 6.1 m−3 of soil removed from ditches and road- ways. Although no records are kept of the number of truck- loads of sediment removed during a ditch/road cleanup, costs for an individual storm in June 2000, were estimated by the DDE at 30,500 for the entire sector (an additional 53,500were required for ditch bank collapse along field edges), suggesting that 100,000 is a conservative annual estimate for the study area. Furthermore, if mean slope length perpendicular to sensitive road sections is estimated at about 300m, the erosion rate for the fields concerned is about 30–35 t ha−1 per year (based on an annual cost of 100,000 , 6.1 m−3, and a bulk density of about 1.3 t m−3), a conservative realistic estimate for the region.

Current erosion control subsidies in the region are of two kinds (Lebrun, 2000). One subsidises the planting of grass strips, the other of hedges. Both these measures are associ- ated with other concerns, most notably nitrate pollution and biodiversity. For grass strips, the subsidy is 380 ha−1 per year (or 456 km−1 for a 12 m grass strip and 912 km−1 for a 24m strip). Crop revenues in the region are about twice that amount, and are estimated at about 700 ha−1 per year; the difference in revenue explains the low farmer participation. Plants for the hedge are fully subsidised by a local government agency but planting is at the expense of the farmer, total cost for implementing this measure (plant and planting costs) is about 6 m−1 of hedge.

The beneficial effects of grass strips in filtering nu- trients, pesticides, and sediments from runoff has been proven (Hayes et al., 1984; Vought et al., 1995; Emama Ligdi and Morgan, 1995; Desta Tadesse and Morgan, 1996; Munoz-Carpena et al., 1999; Deletic, 2001). Reduction rates vary from about 50 to 95% depending on vegetation type, strip width, upslope inclination and area, and rainfall characteristics. Initial results from a current experimental trial in the study area on one of the high risk road sections suggest that a 12 m wide strip combined with a hedge along the field edge might be

enough to entirely eliminate sedi- ment deposits on the roadway. However, the trial has only just begun and more time is needed to confirm this result.

Since no data were available on the impact of grass strips under local conditions, the RUSLE model (Renard et al., 1994; Renard et al., 1997) was used to simulate different grass filter strip widths and slope angle combinations us- ing data for the local climate, soil, and agricultural context. Rainfall erosivity was estimated based on a 30-year monthly rainfall record (Renard and Freimund, 1994). Soil erodibil- ity was calculated using soil texture and organic matter data. The management index (crop type and agricultural tool se- quence) was calculated by adapting the default "corn" file provided to local planting and growth rate dates and to cul- tivation sequences (Renard et al., 1997). The "dense grass" default file was used to simulate the grass strip. A standard convexo-concave topographical profile was used where the straight midslope section inclination was fixed at 10%. Since the DEM probably underestimated slope slightly in the topo- graphic controls on roadway deposition, and since the slope in the slope– length combinations retained refers to the min- imum slope, a 10% slope was considered more representa- tive of actual slope conditions than the minimum. Simula- tions were run for 20 and 30% slopes and the proportion of sediments retained by the filter strips increased with increas- ing slope. Midslope distance from the road and downslope section inclination were kept at 150 m and 2%, respectively, for all simulations. Altering the downslope length between 125 and 200 m had no effect on the proportion of sediments trapped for the 10% slope.

The objective of the simulations was to estimate soil loss reduction for 12 and 24 m width grass strips: these widths were chosen to correspond with the common 12m seed planter width (12 m = 1 tractor pass, 24 m = 2 passes). All of the simulations were run with sunflower as the crop ups- lope of the grass strip since this is by far the most common crop generating sediment deposition problems.

Table 2
Costs and savings associated with planting grass strips on the entire predicted road length: summary for the first year of planting

Slope (%)–length (m)	Grass strip (m)					
	12			24		
	Planting cost (€)	Reduction in cleanup costs (€)	Net savings (€)	Planting cost (€)	Reduction in cleanup costs (€)	Net savings (€)
6–125	15732	15930	198	31464	26881	−4583
6–150	18058	19031	973	36115	32115	−4001
6–175	19015	20581	1566	38030	34731	−3299
6–200	21158	22837	1679	42317	38537	−3779
7–150	15641	16211	571	31282	27357	−3925
7–175	17009	17621	612	34018	29736	−4282
7–200	19471	21004	1533	38942	35445	−3497
8–200	16234	18326	2092	32467	30925	−1542

The RUSLE model predicted that the grass buffer strips trapped 32 and 54% of eroded sediments for the 12 and 24 m strips, respectively, for an erosion rate of 28 t ha−1 on the 10% midslope section. Although few field measurements of erosion have been made (test plots have never been set up in the area), erosion rates appear realistic based on rill erosion measurements carried out on a half dozen fields in 1997 and 1998 (Bruno and Fox, 2003). The grass filter ef- ficiency (percentage of eroded sediments maintained within the field) appears to be relatively low compared to values cited in the literature (cited above), but direct comparisons are impossible due to the different experimental conditions. This, however, suggests that actual benefits from planting grass strips might be greater than anticipated based on the results presented here.

Costs were estimated for two time periods: the initial year of planting, and the upkeep of the grass strip during subsequent years. Cost of planting for the initial year was based

on planting grass strips on the entire road length pre- dicted by the slope–length combination (including falsely predicted segments); upkeep for subsequent years is es- timated at 10% of the initial planting costs (for farmers with livestock, the grass strip becomes a source of forage in subsequent years and may actually represent a source of savings). The savings in cleanup costs were based on a 32% reduction in soil loss for the 12m grass strip and 54% reduction for the 24m strip, as predicted by the RUSLE simulations. The reduction in cleanup costs were then calculated for the correctly predicted road segments only.

The results of the calculations are summarized in Table 2 for the initial year and Table 3 for subsequent years. It should be noted that all the estimates lean toward the conservative side, so actual savings would probably be greater than the values cited here. For the first year (Table 2), the cost of planting 12 m grass buffer strips along the entire length of the predicted road sections is slightly less than the current cleanup costs, estimated at about 100,000 per year. The 8%–200 m combination has the greatest savings (2092 euros). For the 24 m grass strips, the cost of planting the strips is actually greater than the cost of cleaning the roadways, and losses range from 1542 to 4583 euros.

After the first year, planting costs are eliminated and only buffer strip upkeep needs to be taken into account. The val- ues in Table 3 show that savings in subsequent years are substantially greater than the first year. In this case, it is the 6%–200m combination that provides the greatest savings for both the 12 and 24 m grass strips. The most cost-effective combination in the first year is the one that minimizes the expense of planting grass strips on falsely predicted roads. Afterwards, the best combination is the one that maximizes correctly predicted road sections.

Table 3
Costs and savings associated with planting grass strips on the entire predicted road length: summary for subsequent years

Slope (%)–length (m)	Grass strip (m)					
	12			24		
	Upkeep cost (€)	Reduction in cleanup costs (€)	Net savings (€)	Upkeep cost (€)	Reduction in cleanup costs (€)	Net savings (€)
6–125	1573	15930	14356	3146	26881	23735
6–150	1806	19031	17225	3612	32115	28503
6–175	1902	20581	18680	3803	34731	30928
6–200	2116	22837	20721	4232	38537	34306
7–150	1564	16211	14647	3128	27357	24229
7–175	1701	17621	15920	3402	29736	26334
7–200	1947	21004	19057	3894	35445	31551
8–200	1623	18326	16703	3247	30925	27678

Although the savings do not fully compensate farmer rev- enues, they can contribute to make the buffer strips more attractive. In addition, if only the affected roadways were planted with a grass strip, the savings would compensate entirely the loss in revenues to the farmers and would be sufficient to pay for the entire subsidy. The predicted values in Tables 2 and 3 therefore represent worse-case scenarios and actual savings would probably be substantially greater as a function of both soil retention by the buffer strips and a more strategic use of grass strips.

Adding a hedge to the grass strips would cost about 126,000 euros for the hedge alone, which is greater than the current estimated cleanup cost of 100,000 euros. The beneficial effects of hedges on reducing sediment delivery are practi- cally impossible to estimate, so the high initial cost of plant- ing justifies a more thorough study before proposing it as a conservation measure. However, in addition to trapping sediments, a hedge would probably reduce the high costs associated with ditch bank collapse not taken into account in this study.

5. Conclusions

Erosion control strategies often fail because subsidies are insufficient to motivate farmers and because farmer erosion awareness is generally low. An alternative approach to cur- rent erosion control strategies is to concentrate initially on high risk zones which generate immediate public costs. In the study area, savings from reduced road cleanups can con- tribute significantly to compensate farmers for planting and maintaining grass strips along problem road sections. Al- though this does not prevent the more serious problem of soil degradation, it initiates erosion control strategies which can be used as demonstration plots for more general appli- cation. Grass strip efficiency was relatively low in the model results provided here and there is some hope that actual re- ductions are greater than the predicted values. This point needs further study, as does the specific effects and benefits of a hedge. In addition to the impact on sediment delivery, the effects on bank stabilisation and biodiversity would need to be considered.

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