Agroforestry Systems **21**: 191–211, 1993.

Performance of biological erosion control in New Zealand soft rock hill terrain

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Key words: erosion control, silvopastoral land use, gully erosion, mass movement, evaluation

Abstract. An investigation of the performance of biological erosion control measures applied to support pastoral land use in soft rock hill country has yielded information which can be applied in the design of more sustainable, silvopastoral land uses. Vegetation-based treatments, centred particularly on use of fast-growing poplars and willows, have successfully controlled a range of gully erosion and earthflow mass movement problems. Treatments were found to be successful at 63% of earthflow sites, and 42% of gully erosion sites examined, using an evaluation technique known to be conservative. A total of 278 sites were included in the study. Relationships between performance and site and treatment attributes allowed minimum tree configurations to be specified in terms of tree spacing and coverage of erosion landforms. Although further data collection would allow refinement of these minimum specifications, the need for such data depends on the value of tree crop versus pastoral production.

Introduction

Plantation forestry or a two-tier pasture-tree crop land use are now widely regarded as the essential land use options for much of New Zealand's erosion-prone soft rock hill terrain. Widespread landslide, gully and earthflow erosion associated with pastoral land use has led to increasing concern that pastoral farming is unsustainable in large areas of land where indigenous forest was cleared by European settlers to allow sheep and cattle farming [17].

There is evidence that in many areas forestry land use can greatly reduce erosion [4, 10, 12, 21]. This, together with the desire for land use diversification and a social need for land uses which match the skills and inclinations of the landowners, has led to interest in silvopastoral systems. Successful application of the concept of silvopastoral land use depends on knowledge of minimum tree-planting configurations for land stability, and the extent to which trees need to be supplemented by other practices to contain erosion. However, such knowledge is sparse [11, 20].

This paper addresses this need for improved knowledge of the impacts of trees on slope stability in sub-forestry planting configurations, through examination of the performance of biological erosion control at 278 sites of gully and earthflow erosion. The sites are located in the Gisborne-East Cape region of New Zealand (Fig. 1) where erodible, weak (but commonly fertile) soil and rock materials, tectonically active terrain and susceptibility to cyclonic storms combine to produce New Zealand's most severe erosion problems in pastoral land [2]. Fieldwork for the study was carried out in 1989—91, after a particularly severe tropical cyclone (Cyclone Bola, 1988).

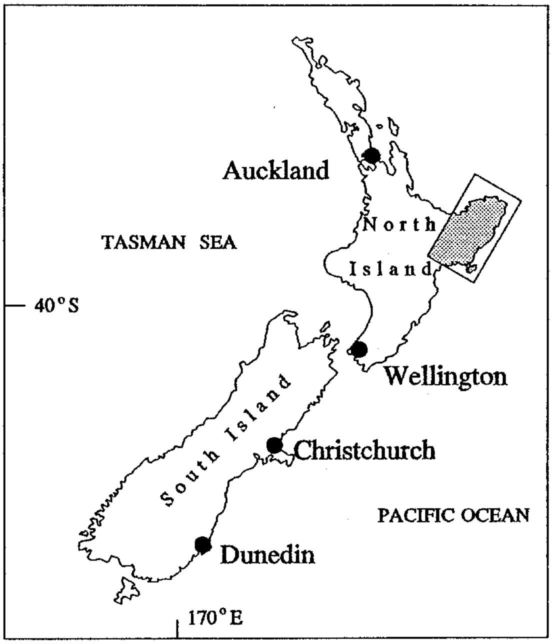

Fig. 1. Location map of the Gisborne-East Cape region, New Zealand.

Biological erosion control measures in pastoral land (Fig. 2) have centred on various poplar and willow species [18], together with localised timber forest plantations, usually of Monterey pine (*Pinus radiata*). Commonly, these techniques have been supplemented by non-biological techniques, including debris retention structures and (less commonly) surface and sub-surface drainage. Most farm erosion control has been directed at gully and earthflow erosion affecting the more productive, less steep, terrain classes, and consequently this paper has less relevance to sustainable land use in steep terrain prone to rapid, storm-induced landslides.

Gully and earthflow erosion affecting pastoral land

Erosion mapping has shown that gully and earthflow erosion have similar distributions in the Gisborne-East Cape region [2]. This reflects their tend-

Fig. 2. Pastoral hill land underlain by Tertiary mudstone, showing biological stabilisation (using *Salix* sp.) of eroding gullies and earthflows.

ency to be mutually dependent. Most activity occurs in weak lithologies — primarily Tertiary mudstones prone to slaking (rapid disintegration when subject to cyclic wetting and drying) and, to a lesser extent, alternating sandstone-mudstone sequences and marls. Bentonite and bentonitic mudstone occur less frequently, but because of their ability to absorb water and swell dramatically, they exhibit some of the most extreme erosion. Very severe cases of erosion also occur in older (Lower Tertiary or Cretaceous) argillites, some of which have been greatly weakened by folding and faulting.

Soils are dystrocrepts, eutrocrepts, hapludalfs, and udivitrands [15]. Mean annual rainfall is 1600—1800 mm for the larger portion of the region, but can be as low as 1000 mm [9]. Rainfall is unevenly distributed throughout the year with a prominent winter maximum. The region experiences major storms of tropical (e.g. Cyclone Bola, in 1988) and polar origin [6]; such storms commonly exacerbate gully and landslip erosion, but are of less immediate consequence to earthflow erosion. The area comprised dense native forest (broadleaved species and podocarp conifers) in pre-European times; removal of this vegetation cover is considered the most immediate cause of the erosion, which nevertheless has a high natural (or 'geological') component [3].

Gully erosion

Gullies vary in depth from less than two to more than ten metres, and channel slopes range from very steep (more than 20 degrees) to shallow (less than 5 degrees). Water flow in the channels is commonly seasonal. Factors exacerbating erosion following conversion of forest to pasture include increased surface water movement (as a result of reduced rainfall interception, and lower infiltration capacities of the soils under pasture), increased mass movement (exposing greater areas of disturbed, unvegetated soil to surface water, and supplying unconsolidated debris to the gully margin), livestock trampling in wet areas prone to gullying (degrading the turf mat, exposing the soil to surface erosion processes), precarious stability of oversteepened gully walls produced by undercutting and removal of stabilising vegetation), and more rapid weathering, both physical (slaking) and chemical (dissolution of cementing agents).

Earthflow erosion

Here we use the term 'earthflow' for 'earth slump', 'earthflow' and 'slump-earthflow' as defined by Varnes [19]. Earthflow movement is mostly slow, persistent and commonly seasonal [7], and typically occurs on slopes less than 25 degrees. Movement depths are difficult to determine from surface observations, but are generally 2—10 m. While there is much internal deformation, most movement occurs along a well defined basal slip surface. Response to rainfall is usually slow because of the depth of movement and low permeability of the materials. Moving terrain tends to be considerably wetter and weaker than non-moving ground. This may be due to clay swelling, loosening of regolith fabric by deformation, or to removal of soluble components [16]. All of these processes are likely to be coupled to some degree.

Root system decay, decreased evapotranspiration, surface desiccation and cracking (enhancing water access to potential failure zones), faster weathering, and removal of toe support (by gullying, or other mass movement), probably all contributed to increased earthflow activity following forest removal. Medium term climatic variability is also thought to affect earthflow activity.

Classification

For the purposes of this study, gully and earthflow erosion forms have been grouped according to Fig. 3. This classification is somewhat arbitrary, but is useful in the context of land management, and does reflect the close association of the two erosion forms.

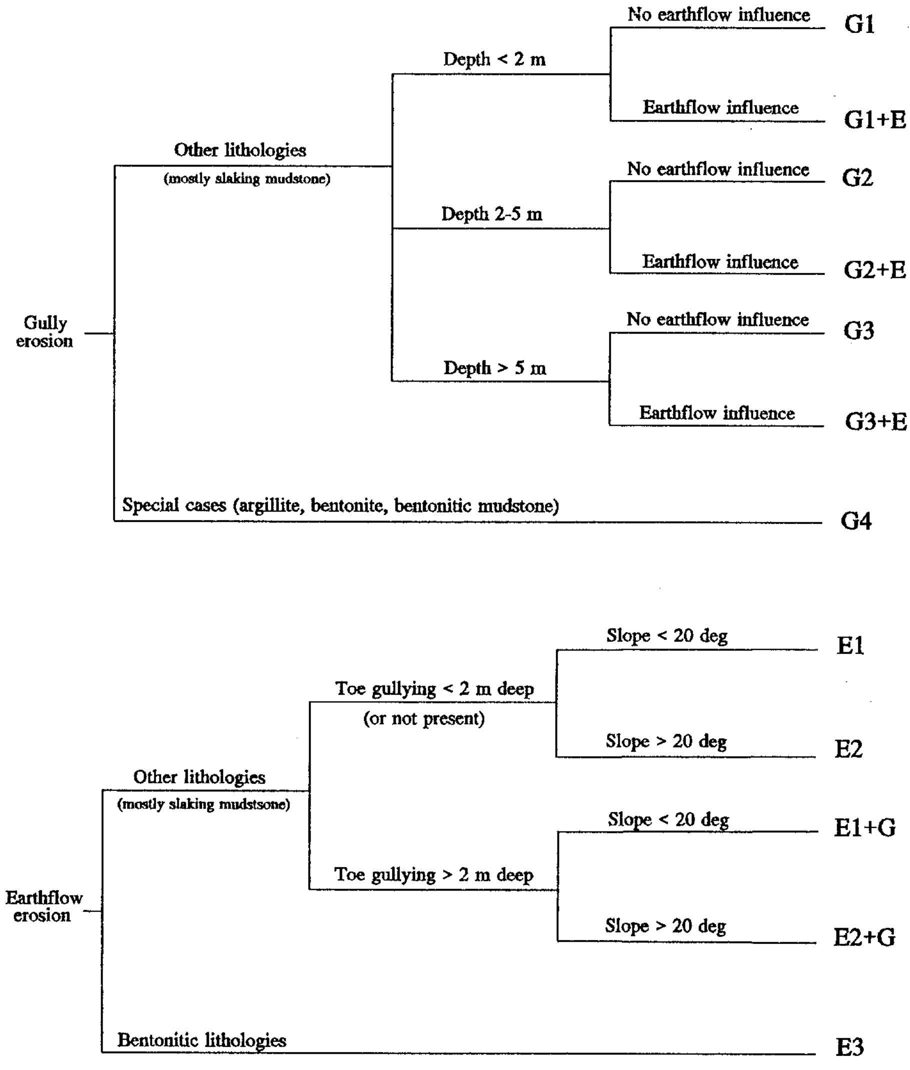

Fig. 3. Site classifications for gully and earthflow erosion. Earthflows 'influence' gully erosion if they feed into a substantial part of the gully system or create important new sites for gullying through tension cracking or weakening of material in lateral shear zones; they may dominate gullying by providing continuous replenishment of erodible material, with the potential to overwhelm stabilisation measures confined to the gully system.

Biological erosion control

The variety and complexity of interacting processes determining land stability in soft rock terrain has ensured biological erosion control. It has always been approached empirically; basic studies of stabilisation mechanisms and processes have assisted in conceptual overviews but have always failed to produce confident recommendations for biological erosion control.

Table 1 summarises the techniques commonly employed to control gully and earthflow erosion in the Gisborne-East Cape region. As the techniques are often applied in combination, the generalised erosion treatment classifications shown in Fig. 4 are used as the framework for this study. Classes convey not only the type of treatment employed, but also the extent to which it was applied.

Table 1. Techniques commonly used to control gully and earthflow erosion in soft rock terrain in the Gisborne-East Cape region, New Zealand.

Gully erosion	Earthflow mass movement
Forestation	Forestation
Gully wall planting	Space-planted trees
Channel (or pair) planting	Localised close planting
Debris retention dams	Gully control at toe
	Graded diversion banks
	Surface smoothing
	Horizontal subsurface drains
	Spring taps

Gray and Leiser [5] and Sidle et al. [14] discuss use of vegetation for erosion control. Van Kraayenoord and Hathaway [18] describe poplar and willow species employed in New Zealand. Poplars include *Populus alba, P. deltoides, P. nigra* 'Italica', Italian *deltoides* × *nigra* hybrids (*P.* × *euramericana*), of which I-78, I-214, and I-455 were most widely used, American balsam and black poplar hybrids, and the Dutch 'Flevo' poplar. Willows include *Salix matsudana, S. matsudana* × *alba* (hybrid tree willows), *S. babylonica* (weeping willow), *S. fragilis* (crack willow), and *S. alba* var. *vitellina* (golden willow).

Gully erosion

Tree planting along the gully channel (commonly as 'pair planting', with trees in pairs on either side of the stream channel) is intended to strengthen channel margins against slumping and scour and provide a strong scour-resistant root mat for the gully channel. The partially exposed root mat tends to restrict movement of sediment (depending on particle size and water velocity), with roots functioning as debris traps. Debris dams also restrict flow of debris from the catchment and reduce channel gradients. Sediment deposition behind these dams raises the channel base level, thus improving channel wall stability. Debris dams are usually used in association with tree planting and the need for them may be reduced when the trees mature. Wall

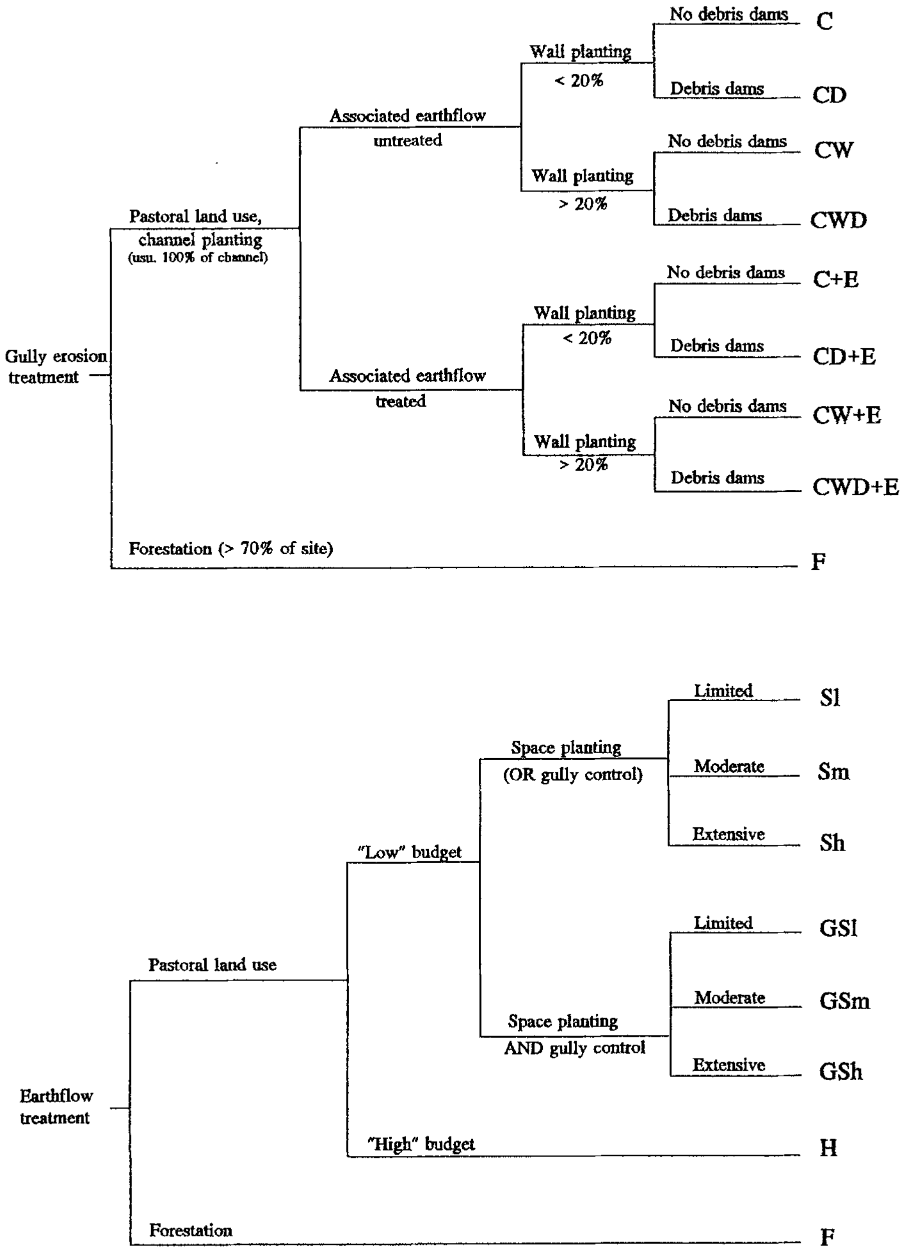

Fig. 4. Treatment classification. 'No debris dams' includes cases where only minor use is made of debris dams. 'Limited' treatment involves only one technique applied at a low intensity or to only a small part of the problem area. 'Extensive' treatment involves intensive treatment of most or all of the land area subject to erosion. The performance evaluation procedure employs scoring to classify individual treatments. 'Low budget' treatments do not include surface smoothing, graded banks, or subsurface drainage measures.

planting, usually with willows, is employed where gullies are deeper and the walls prone to mass movement.

Forestation with *Pinus radiata* may result in rainfall interception rates of up to 35% [14], leading to reduced streamflow and hence reduced channel scour. Forest litter provides a second level of interception, and a measure of protection against rain-splash erosion and scour from overland flow. Tree root networks, regardless of species employed, increase the rigidity of the regolith and hence reduce cracking which might have led to further gullying.

Earthflow erosion

Intermittently moving or creeping earthflows are marginally unstable, and it is possible that a relatively minor stabilization treatment (such as gully erosion control at the toe) may be sufficient. However, the tendency for the strength of the compacted clays forming mudstone regoliths to decline with time suggests such minor measures would not provide long term solutions.

In space-planting, poplars or willows are planted at spacings sufficiently wide to allow pastoral use. For more active, continuously moving earthflows, spacings may be less than 5 m and the treatment is termed close-spaced planting. *Pinus radiata* may be used with the intention of later harvesting. Timber forests or widespread close-planting are grouped under the term forestation.

Tree transpiration has a direct effect on subsoil moisture regimes, whereas pasture transpiration has a primarily indirect (and therefore potentially lower) effect on subsoil moisture, as most moisture is extracted directly from surficial soils. Subsoil moisture levels may also be significantly altered by rainfall interception. Root systems may improve stability by increasing regolith rigidity through reinforcement and transpiration-induced plastic density increases [1, 13]. Such plastic density increases could contribute to improved stability beneath deciduous trees during wet periods. However, there is uncertainty that tree roots penetrate deeply enough in sufficient numbers to significantly alter resistance along the basal failure surface of many earthflows.

Where potential productivity gains warrant it, earthflows may be cultivated, smoothed and regrassed. Graded banks may be installed to divert surface water, and spring taps or horizontal bores installed to reduce pore water pressures. Non-biological techniques are usually supplemented by tree planting.

Evaluation of treatments

Treatments were evaluated at 278 sites — 136 gully erosion sites and 142 earthflow erosion sites. Sites were selected taking account of: parent lithology (although most were underlain by Tertiary slaking mudstone), accessibility, age of the stabilisation measures, and the type of treatment employed. Although the range of sites examined is a substantial cross section of the erosion problems for which biological control has been considered feasible, not all types of problems present in the Gisborne-East Cape region are represented.

Sites were generally small (less than 10 ha) and comprised identifiable erosion entities — individual or groups of gullies or earthflows whose status was determined primarily by on-site effects. At most sites, treatments had been installed for between 10 and 30 years. Given the large number of sites examined and the usual treatment age, natural tendencies towards greater stability of mass movements or chance avoidance of the most severe erosion-producing events are unlikely to have affected the results significantly. Although sites were clustered to some extent, our data do not show any evidence of dependence on local variations in cyclonic or other rainfall.

For each site, a standard dataset (Appendix) describing both the site and treatment was collected, mostly by direct field observation. A multi-choice format was used for most data items, including all those requiring a descriptive verbal response; this provided a degree of standardisation which assisted comparisons between sites. Some historical data was obtained from landowners, local research staff, and soil conservators. Rather than rely on a direct subjective assessment of the success or failure of the treatments, data was interpreted using formal inference-based procedures described by Luckman and Thompson [8], and summarised in Fig. 5. Separate procedures exist for earthflow and gully erosion control, although many of the inferences are common to both. Probabilistic techniques are employed to deal with the uncertainty inherent in assessments of stability and erosion rate. Evidence is combined using conditional probability, Bayesian updating, rules, decision trees, and scoring systems.

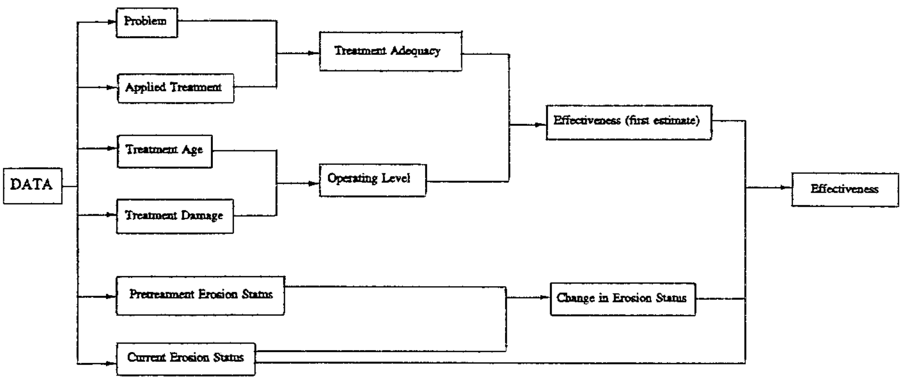

Fig. 5. Procedure for evaluating performance of biological erosion control treatments. Inferences involving 'data' tend to be specific to the erosion type; others are independent of erosion type.

Performance is assessed in terms of 'effectiveness', defined as the degree to which the land has been returned to a state of minimal erosion by the stabilization methods employed. Effectiveness is expressed initially using six classes defined as follows:

I (*nil or negligible*)
- little or no effect on erosion status.

II (*very low*)
- an observable improvement in land stability attributable to the treatment.

III (*low*)
- significant improvement in land stability attributable to the treatment;
- substantial or very substantial continuing erosion;
- agricultural use significantly or severely impaired.

IV (*moderate*)
- significant improvement in land stability attributable to the treatment;
- mostly or completely stabilised;
- past erosion is the main determinant of land condition;
- previously eroded areas should at least be in the early stages of recovery.

V (*satisfactory*)
- significant improvement in land stability attributable to the treatment;
- mostly or completely stabilised;
- past erosion is the main determinant of land condition;
- previously eroded areas should be substantially recovered.

VI (*very satisfactory*)
- major improvement in land stability attributable to the treatment;
- mostly or completely stabilised;
- past erosion is the main determinant of land condition;
- previously eroded areas should be substantially recovered.

For the purpose of this study, we designate effectiveness classes V and VI as 'successful', and others as 'unsuccessful'. Other definitions might allow class IV as 'successful'. Our emphasis on the requirement for returning the site to a state of minimal damage prevents this. Figure 6 illustrates graphically the relationships between erosion damage, activity (i.e. rate or risk of new damage), time, and performance (or effectiveness) of erosion control treatments.

The evaluation procedures calculate a probability for each effectiveness class. The class with highest probability is here used as the measure of effectiveness. A feature of the evaluation procedures is the fact that they make allowance for prior knowledge of the effectiveness of different treat-

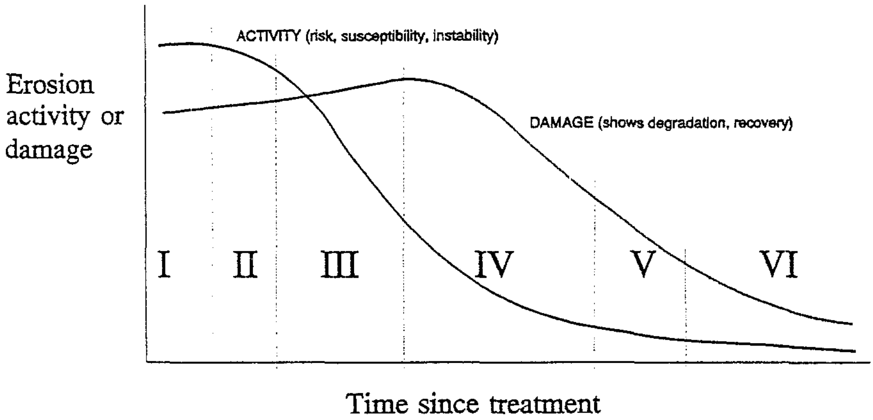

Fig. 6. Conceptual relationships between erosion activity, damage, time and the performance (effectiveness) of erosion control treatments. Effectiveness classes I through VI are defined in the text.

ments, and also take account of trends in the state of the treatments themselves (e.g. the health and age of the trees). This is a commonsense approach, appropriate when hard data are sparse, but has tended to produce slightly conservative results [9]. The procedures are automated, and produce verbal site reports, graphs of the essential results, and a summary of all observations and conclusions in a PC-database.

Results

Tables 2 and 3 relate the performance of erosion treatments to site and treatment classifications shown in Figs. 3 and 4. These Tables also reveal the scope of each treatment class, as perceived by erosion control practitioners, and can be used to estimate the probability of success of particular site-treatment combinations. More detailed analysis is presented in Tables 4—6 (gully erosion) and Table 7 (earthflow erosion).

Gully erosion

Gully erosion treatments were successful at 42% of the sites; 31% achieved a moderate (Class IV) effectiveness rating. Of the more poorly performing sites, eight had treatments less than 10 years old.

Shallow gullies (depth less than 2 m)
Most of the shallow gullies were essentially unaffected by earthflow activity (G1 sites). Channel planting (treatment C) at these sites generally led to either moderate or satisfactory effectiveness (Table 2). Similar performance

Table 2. Site-treatment dependence of success of biological gully erosion control treatments.

Site class	Gully treatment class								
	C	C+E	CW	CW+E	CD+E	CWD	CWD+E	F	Total
G1	18/35	1/5	4/4	0/2	—	—	—	2/2	25/48
G1+E	2/6	3/10	0/1	1/2	1/1	—	—	—	7/29
G2	1/14	2/5	5/7	0/4	—	—	2/2	1/2	11/34
G2+E	0/1	2/4	0/1	3/5	0/1	1/1	4/6	3/4	13/23
G3	0/2	—	0/3	0/1	—	—	—	—	0/6
G3+E	—	—	—	0/10	—	—	1/1	—	1/2
G4	—	—	—	—	—	—	—	0/3	0/3
Total	21/58	8/24	9/16	4/15	1/2	1/1	7/9	6/11	57/136

Table shows the number of sites successfully treated in relation to the total number of cases examined (number successful/number of sites), for each site-treatment combination.

Table 3. Site-treatment dependence of success of biological earthflow stabilisation treatments.

Site class	Earthflow treatment class								
	Sl	Sm	Sh	GSl	GSm	GSh	H	F	Total
E1	2/12	9/18	9/9	—	1/3	9/10	2/2	1/1	33/55
E2	1/8	4/11	6/7	0/1	1/3	9/9	1/1	1/2	23/42
E1+G	0/1	0/2	—	—	1/3	14/15	4/4	3/4	22/29
E2+G	—	—	—	—	0/1	11/12	—	—	11/13
E3	—	—	—	—	—	—	0/1	1/2	1/3
Total	3/21	13/31	15/16	0/1	3/10	43/46	7/8	6/9	90/142

Table shows number of sites successfully treated in relation to the total number of cases examined, for each site-treatment combination.

was achieved where the site was affected by earthflow activity (G1+E sites), regardless of whether or not the earthflow was treated.

The relationship between downstream tree spacing and treatment performance for treatments C and C+E is shown in Table 4. Of the 10 shallow gully sites with tree spacings of 2—4 m, nine were rated successful. Increasing spacing to 4—8 m led to more variable results — only 11 of the 32 sites with this greater spacing were rated satisfactory, moderate being more common. Further increasing spacing to 8—12 m led generally to moderate effectiveness ratings. At two of the three sites with spacing greater than 12 m, erosion control was successful, apparently contradicting the trend.

There were nine sites to which both channel and wall planting, either with

Table 4. Dependence of stabilisation success on gully depth and the downstream tree spacing, for gullies less than 5 m deep treated by channel planting (treatments C, C+E).

Tree spacing	Gully depth		
	< 2 metres	2—5 metres	Total
2—4	9/10	3/7	12/17
4—8	11/32	2/14	13/46
8—12	2/11	0/3	2/14
> 12	2/3	—	2/3
Total	24/56	5/22	29/80

Table shows the number of sites of successful treatment in relation to the total number of cases examined (number successful/number of sites), for each depth — tree spacing combination. (< 2 m gullies are G1, G1+E sites; 2—5 m gullies are G2, G2+E sites.)

Table 5. Dependence of gully stabilisation success on gully depth, downstream spacing of channel planting, and percentage of eroding gully walls treated by wall planting, for gullies treated with a combination of both channel planting and wall planting (treatments CW, CW+E). Most wall planting is carried out at 4—8 m spacing.

Gully depth (m)	Channel planting spacing (m)	Percentage of walls planted with trees					
		⩽ 20	21—40	41—60	61—80	> 80	Total
< 2	< 2	—	—	—	—	—	—
	2—4	—	1/1	—	—	—	1/1
	4—8	—	0/2	1/1	1/1	0/1	2/5
	8—12	—	2/2	—	—	0/1	2/3
	Total	—	3/5	1/1	1/1	0/2	5/9
2—5	< 2	—	—	—	—	2/2	2/2
	2—4	—	1/2	2/3	—	—	3/5
	4—8	—	0/3	1/1	3/4	0/1	4/9
	8—12	—	—	0/1	—	—	0/1
	Total	—	1/5	3/5	3/4	2/3	9/17
Total		—	4/10	3/6	4/5	2/5	14/26

Table shows the number of sites of successful treatment in relation to the total number of cases examined (number successful/number of sites), for each combination of conditions.

(CW+E) or without (CW) associated earthflow treatments, were applied to shallow gullies; erosion control was successful at five of these (Table 2). The effectiveness of different combinations of channel planting spacing and wall coverage is variable (Table 5), the sample size being too small for trends to be seen.

Forestation of shallow gullies was successful at two sites.

Table 6. Treatment attributes of gullies (depth >2 m) treated with a combination of channel planting, wall planting, and debris dams (treatment classes CWD and CWD+E).

Performance	Downslope spacing, channel planting (m)	Wall coverage (%)	Spacing of wall planting (M)	Debris dams
Successful	2–4	21–40	<4	Subst.
	2–4	41–60	4–8	Subst.
	4–8*	41–60	4–8	Signif.
	4–8	all	4–8	Subst.
	2–4	21–40	<4	Subst.
	2–4	all	4–8	Subst.
	4–8	all	4–8	Subst.
	4–8	all	4–8	Subst.
Unsuccessful	4–8	(unknown)	4–8	Signif.
	4–8	21–40	4–8	Subst.

(Note: 'significant' usage of debris dams implies debris dams installed so as to reduce grade and restrain debris in most of the more important (steeper, more eroding) gully sections; 'substantial' implies dams installed in all such sections. Gully depth for all sites is 2–5 m, except site marked with asterisk, where depth exceeded 5 m.)

Deep gullies (depth 2–5m)

In these deeper (G2, G2+E) gullies, channel planting alone generally produced ratings less than 'satisfactory' (Table 2). Of the five cases where this treatment was successful, all had relatively close tree spacings (2–4 m or 4–8 m, Table 4), and for four the associated earthflows had also been treated (Table 2).

Combined channel and wall planting (treatment CW), usually with wall planting spacing 4–8 m, was successful more frequently than channel planting alone (Table 2). G2 sites treated with CW+E did not display this trend; possibly sites to which the additional earthflow treatment was applied were more difficult to stabilise.

Table 5 shows the effects of varying downslope spacing of channel planting and the amount of wall planting, for deep gullies. With 4–8 m or closer channel planting spacing and more than 60% wall coverage (with a typical spacing of 4–8 m), five out of seven sites were successfully stabilised. With more than 40% wall coverage and the same channel planting spacings, eight out of eleven sites were successful. For lower wall coverage, ratings were generally less than satisfactory (four out of five sites).

Supplementing wall and channel planting with debris dams (installed to reduce grade and restrain debris in most or all of the steeper, more eroding gully sections), also resulted in a high success rate (seven out of nine) when applied to deep gullies. Details of the various components of treatments in the sites are summarized in Table 6.

Forestation applied to deep gullies was generally successful (4 our of 6 sites, Table 2).

Table 7. Dependence of success of earthflow stabilisation on extent of planting of the earthflow area, and treatment of gully erosion at the toe.

Depth of gullying at toe (m)	Treatment classes	Tree spacing (m)	Percentage of earthflow planted					
			≤20	21–40	41–60	61–80	>80	Total
		3–5	—	1/1	—	—	3/3	4/4
	Sl	5–8	1/1	2/8	2/5	12/12	2/3	19/29
	Sh	8–10	0/1	0/2	3/6	2/5	2/6	7/20
	Sm	>10	1/3	0/4	0/1	0/1	1/1	2/10
		Total	2/5	3/15	5/12	14/18	8/13	32/63
<2		3–5	—	—	—	3/3	0/1	3/4
	GSl	5–8	—	1/1	—	6/6	6/6	13/13
	GSm	8–10	—	—	2/2	—	1/1	3/3
	GSh	>10	0/1	—	—	0/4	1/1	1/6
		Total	0/1	1/1	2/2	9/13	8/9	20/26
	Total		2/6	4/16	7/14	23/31	16/22	52/89
	Sl-Sh	All	—	0/1	—	0/2	—	0/3
		3–5	—	—	1/1	—	2/2	3/3
	GSl	5–8	—	3/3	2/3	5/6	9/9	19/21
>2	GSm	8–10	0/1	0/1	—	2/3	2/2	4/7
	GSh	>10	—	—	—	—	1/1	1/1
		Total	0/1	3/4	3/4	7/9	14/14	27/32
	Total		0/1	3/5	3/4	7/11	14/14	27/35
Total			2/7	7/21	10/18	30/42	30/36	79/124

Table shows the number of sites of successful treatment in relation to the total number of cases examined, for each attribute combination.

Very deep gullies (depth exceeding 5 m)
Only 8 very deep gully sites were included in the study (Table 2). None of these were forested. Channel planting alone, and channel and wall planting combined (both with and without earthflow treatment), were unsuccessful treatments. The only site where treatment performed satisfactorily had been treated comprehensively by channel planting, wall planting, and debris dams; the associated earthflow was also treated.

Special cases (bentonitic or argillite lithologies)
Only three gullies in bentonite and argillite were investigated (Table 2). All three sites had been forested, but the treatment did not perform satisfactorily at any of these.

Earthflow erosion

Earthflow erosion control treatments were rated successful more often than gully control treatments. 63% of the earthflow sites were successful; 33% were rated moderate. Only five of the sites (4%) did not achieve an effectiveness rating of moderate or better, and of these, 2 were less than 9 years old.

Earthflows with minor (or no) gullying at toe
Table 3 shows that more extensive treatments have produced more effective results, and E1 and E2 sites do not appear to have responded differently.

Table 7 shows tree spacing and percentage of earthflow area covered for sites with treatments other than 'high budget' or forestation (H or F). Earthflow sites with shallow untreated toe gullying (included in Sl, Sm, and Sh) were successful where spacing was 3—5 m, or with 5—8 m spacing if coverage exceeded 60%. Increasing spacing to 8—10 m, with the same coverage, reduced the success rate (4 out of 11) and only 2 of ten sites with spacing exceeding 10 m were successful.

Where gully stabilisation was used to supplement space planting of the earthflow, results were broadly similar (Tables 3 and 7). However, with the associated gullying treated, wider tree spacings and less cover appeared to produce equivalent success rates: tree planting at spacings of 8—10 m with more than 40% coverage was successful, and 5—8 m spacing appeared successful providing coverage exceeded 20% (the one site with 21—40% coverage and 5—8 m spacing was successful). Five of the six sites where ratings were less than 'satisfactory' had tree spacings exceeding 10 m.

The three 'high budget' (H) treatments, and two of the three forestation (F) treatments, were also successful when applied to sites with minimal toe gullying (Table 3).

Earthflows with deep gullying at toe
Again, there is a clear tendency for erosion control performance to increase with the extent of the treatment. Results for both E1+G and E2+G sites are very similar. Space planting and gully control were used in combination at most of these sites. In the three cases where space planting alone was applied (i.e. where the significance of the gullying was not recognized), performance was rated less than satisfactory (Table 3).

Relatively extensive treatments involving both gully and space planting (GSh) appear necessary for successful performance (Table 3). Tree spacing and percentage cover are shown in Table 7. Successful stabilisation was achieved where tree spacings were 3—5 m or 5—8 m (provided coverage exceeded 20%). Wider (8—10 m) spacing required more than 60% coverage.

'High budget' (H) treatments were successful, as were most cases of forestation (F) treatment (Table 3). The one apparently unsuccessful forestation treatment was less than 10 years old.

Special cases

Only three sites in bentonitic lithologies were examined. One was given the 'high budget' treatment (H) and was rated moderately effective. The other two sites were treated with forestation; one was satisfactory, the other only moderately effective.

Discussion and conclusion

Erosion control performance

Biological control of gully and earthflow erosion problems in soft rock terrain is clearly feasible, even using sub-forestry planting configurations such as might be useful in silvopastoral land uses. Stabilisation was successful at 63% of the earthflow sites and 42% of the gully erosion sites, according to an evaluation technique known to be conservative. Thus, erosion control practitioners have had some success in designing appropriate stabilisation treatments within the constraints of the dominant pastoral land use, although there is room for more efficient use of erosion control resources. Because our definition of erosion control success excluded sites where effectiveness was rated moderate (significant improvement in land stability attributable to the treatment; mostly or completely stabilised; past erosion is the main determinant of land condition; previously eroded areas at least in the early stages of recovery), it is important that these success rates be interpreted carefully.

Feasible treatments exist for 8 of the 12 different problem categories (i.e. for gullies up to 5 m deep, and for earthflows other than those in bentonitic terrain). These treatments are feasible, subject to economic evaluation. Currently, inability in New Zealand to exploit revenue-earning potential (timber, biomass for pulp and energy) of poplar and willow tree species, in particular, detracts from the appeal of these treatments now that central government support for such erosion control has been severely curtailed.

Planning guidelines

Knowledge gained from successful biological erosion control in pastoral environments can be applied in the design of more sustainable, silvopastoral land uses. Effective stabilisation of shallow gullies (depth less than 2 m) requires channel planting at a spacing of 2—4 m over the entire length of the eroding gully. If reduced performance is acceptable, wider spacings may be employed. Deeper gullies (depth 2—5 m) may be stabilised by channel planting (preferably in pairs) at spacings of 4—8 m or less, in combination with planting 40—60% of the gully walls using a similar spacing. An integrated approach combining debris dams (installed so as to reduce grade and restrain debris in all the steeper, more eroding gully sections), wall planting and channel planting, is also successful, as is forestation (typically with *Pinus radiata*). In cases where gully depth exceeds 5 m, or where gullying occurs in bentonitic or argillite lithologies, no suitable biological treatment was identified; combinations of channel and wall planting alone are unlikely to be satisfactory. When treating gully erosion, it is recommended that any earthflows influencing gully erosion should also be treated, although our results are somewhat ambiguous in this area.

Earthflows with toe gullying less than 2 m deep (or not present) may be stabilised by trees planted at spacings 5—8 m or less, covering more than 60% of the earthflow area. Alternatively, it is feasible to reduce planting of the earthflow area to a minimum of 40% at a wider spacing (8—10 m), if an appropriate gully treatment is employed. Where gully depth at the toe exceeds 2 m, an appropriate gully treatment has to be supplemented by planting at least 20% of the earthflow area at spacings up to 5—8 m. A minimum of 60% of the earthflow area needs to be planted if wider (8—10 m) spacings are employed. 'High budget' (H) treatments and forestation are successful in these cases also.

Relevance to other tree species

Results relate particularly to the poplar and willow species used for biological erosion control in New Zealand pastoral land [18]. However, continued breeding of new poplar and willow clones has produced improved varieties for which these guidelines may be over-conservative. Determining the applicability of the guidelines to other tree species depends on understanding the mechanisms through which the treatments achieve erosion control. Poplars and willows are both quick-growing genera, with extensive root systems and, particularly in the case of willows, a tolerance of moist ground conditions. Although the trees are deciduous and without leaves for much of the time when mass movement events are most likely, it cannot be assumed that their impact derives solely through the mechanical reinforcing effect of the roots. The potential for high transpiring trees to cause irreversible increases in density (and hence increases in strength and rigidity) in the vicinity of roots in heavy clay soils suggests that hydrological effects can extend well beyond the growing period. Clearly however, more conservative treatments might need to be employed with trees which are less vigorous and have less extensive root systems.

Refinements

Empirical rules for minimum planting configurations in silvopastoral systems are inevitably uncertain. This uncertainty is important if factors such as the relative values of tree crops and pastoral production dictate a significant pastoral component to the land use (and hence wider average tree spacings). If it is necessary to adopt a minimum planting strategy, it is clearly important to ensure that trees are correctly chosen and targeted to the erosion landforms and processes.

Data 'holes' in the Tables can be used to prioritise new study sites, and rules can be refined by further application of the procedures employed in this paper, perhaps refining site and treatment classifications in the process — e.g. exploiting knowledge of variations in erodibility. There is scope for extension to other New Zealand soft rock regions with histories of biological erosion control, as well as within the Gisborne-East Cape region.

Ultimately, land use decisions depend on many different sources of knowledge on environmental impacts of vegetation. Much of this will be judgemental expertise of the sort required to explain variation in biological erosion control performance for given site-treatment class combinations. Formal site similarity analysis may be one method which will allow more thorough use of the inevitably limited database of case studies, leading to the production of more specific design recommendations. In this approach, recommendations are developed by exploiting similarity (or dissimilarity) with one or more documented cases in the database. This corresponds to the common practice of translating a management plan from a site where it has proved successful, making sensible modifications which take into account local variations in site conditions.

Acknowledgements

The authors gratefully acknowledge the advice and assistance of their colleagues Don Miller and John Hall, as well as that of Trevor Freeman and George Parker (Gisborne Regional Council). Hugh Wilde reclassified the soils according to the U.S. soil taxonomy. Comments from Garth Eyles, Noel Trustrum and Allan Wilkinson led to significant improvements in the manuscript.

Appendix

Table A: Dataset used to develop erosion control performance assessment, gully erosion.

Problem type and pretreatment status ■ Pretreatment gully depth ■ Gully floor slope angle ■ Pretreatment percentage bare ground ■ Pretreatment evidence of sediment mobility ■ Pretreatment degree of branching/formation of a gully network.
Treatment ■ Types of techniques used ■ Extent of use/placement of debris dams ■ Spacing of tree planting on gully walls ■ Percentage of gully walls (in actively eroding gully sections) treated by tree planting ■ Evidence of tree planting on walls, beyond the actively eroding area ■ Downslope spacing of tree planting in gully channel ■ Percentage of gully channel (in actively eroding gully sections) treated by tree planting ■ Evidence of channel planting beyond eroding sections ■ Percentage of gully treated by forestation ■ Extent to which associated earthflow movement was treated.
Current status of treatment ■ Degree of influence of associated earthflow activity on the gully erosion ■ Survival rate of tree plantings on gully walls ■ Survival rate of tree plantings in gully channel ■ Survival rate of forestation plantings ■ Health of tree plantings on gully walls ■ Health of tree plantings in gully channel ■ Health of forestation plantings ■ Percentage of gully wall plantings torn out by erosion ■ Percentage of gully channel plantings torn out by erosion ■ Percentage of forest plantings torn out by erosion ■ Degree of damage to debris dams.
Current erosion status, and change in status ■ Percentage bare ground ■ Evidence of sediment mobility in gully channel ■ Active gully erosion mechanisms ■ Extent of slip erosion on gully walls ■ Evidence of transformation of major slips into debris flows ■ Evidence of continuing gully enlargement ■ Evidence of change in gully depth ■ Evidence of change in degree of branching ■ Specific evidence for improvements in farm performance attributable to stabilization measures.

Table B: Dataset used to develop erosion control performance assessment, earthflow erosion.

Problem type and pretreatment status ■ Lithology ■ Rock slaking (physical weathering) tendencies ■ Field strength estimate ■ Sandstone-mudstone ratio (for alternating lithologies) ■ Degree of bedding plane control ■ Rock mass jointing/spacing ■ Slope angle ■ Depth of movement ■ Pretreatment ground wetness/bogginess ■ Pretreatment degree of surface disruption ■ Pretreatment evidence for active movement downslope ■ Length of earthflow ■ Earthflow length/width ratio ■ Degree of influence (mean depth) of gully erosion at toe ■ Pretreatment amount of gullying within the earthflow.
Treatment ■ Percentage treated by forestation ■ Percentage treated by space-planting of trees ■ Percentage treated by surface contouring/smoothing ■ Percentage treated by graded diversion banks ■ Extent of use of horizontal drains ■ Extent of use of spring taps ■ Extent of use of gully control at toe ■ Evidence of use of other stabilisation techniques ■ Spacing of space-planted trees ■ Degree of influence of gullying on earthflow movement.
Current status of treatment ■ Survival rate of forest plantings ■ Survival rate of space-planted trees ■ Health of forest plantings ■ Health of space-planted trees ■ Percentage of forest plantings torn out by movement ■ Percentage of space-planted trees torn out by movement ■ Degree of damage suffered by graded diversion banks ■ Evidence that spring taps are still functioning ■ Evidence that horizontal drains are still functioning ■ Condition of gully control treatment at toe
Current erosion status, and change in status ■ Percentage bare ground within earthflow perimeter ■ Abundance and degree of definition of scarps ■ Sharpness of slide boundaries ■ Evidence of relatively fresh tension cracking ■ Evidence of tension cracking behind slide boundaries ■ Length and width of tension cracks ■ Current erosion status of gullies at toe ■ Evidence of discharge of earthflow debris into gully at toe ■ Pretreatment degree of influence of gullying at toe on movement ■ Evidence of disruption of fencelines ■ Evidence for change in land area affected by movement ■ Change in erosion status of gullying at toe ■ Pretreatment degree of influence of gullying at toe on movement ■ Specific evidence for improvements in farm performance attributable to stabilization measures.

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