Gully degradation, stabilisation and effectiveness of reforestation in reducing gully-derived sediment, East Coast region, North Island, New Zealand

Mike Marden,1 Alexander Herzig2 and Gregory Arnold*

1 Landcare Research, P.O. Box 445, Gisborne 4040, New Zealand. Corresponding author: Mardenm@landcareresearch.co.nz
2 Landcare Research, Private Bag 11-052, Palmerston North 4442, New Zealand.
* 1944–2009 (in his memory)

Abstract
Gully stabilisation was modelled by measuring the change in ‘active’ gully area before planting with exotic pines and at the end of a ~40-year reforestation period. A degradation model based on DEMs of gullies at differing stages of development was used to calculate sediment production from reforested gullies in both Cretaceous and Tertiary geological terrains. The total volume of gully-derived sediment was calculated at catchment-scale by combining the gully degradation and stabilisation models with GIS-based mapped distributions of gullies in 1957 and 1997, and then expressed as an equivalent percentage of the average annual suspended sediment yield for each of the three largest and heaviest sediment-laden rivers within the East Coast region, North Island. The modelling of gully-derived sediment yields before and after a 40-year reforestation period (1957–1997) provided a measure of the effectiveness of past reforestation efforts in reducing gully-derived sediment yield. These models were then used to forecast potential reductions in gully-derived sediment for future reforestation scenarios.

The probability of gullies stabilising (a measured reduction in ‘active’ gully area following planting with pines) was strongly associated with gully size and the number of years since planting. The probability of gullies of equivalent size stabilising in response to planting is similar in both the Cretaceous and Tertiary geological terrain. Past reforestation has reduced sediment yield by 33%, 17% and 20% in the Waipaoa, Waiapu and Uawa catchments, nonetheless during the measurement period forested gullies in both terrains collectively contributed 55%, 23% and 54% of the total gully-derived sediment yield in these respective catchments. At catchment scale, gully-derived sediment yield in each of the three major catchments could be halved by 2030 and remain constant thereafter if all remaining untreated gullies were reforested before 2020 and no new gullies were initiated during this period. The greatest number of untreated gullies occurs in the Waiapu catchment, where it is expected that sediment yield would decline by 11Mt/year by the end of the modelling period.

Keywords
Gullies, sediment yield, reforestation, East Coast region, North Island.

Introduction
In areas where gully erosion has developed on a large scale, the cost of erosion control often
far exceeds the value of production from the land concerned (NWASCO, 1970), and the most economic way of controlling this kind of erosion is by reforestation (cf. Piégay et al., 2004). Internationally and locally, forests play an important role in reducing the on- and off-site impacts of gully erosion. Many countries have adopted a mix of both hard (engineering) and soft (reforestation) measures to deal with gully erosion, but New Zealand remains unique in that it continues to rely on reforestation to manage gully erosion, with considerable success both at the local and regional scale, particularly in its most erosion-prone areas such as the East Coast region of the North Island (Phillips and Marden, 2005) (Fig. 1).

Figure 1 – Location map of Waipaoa, Waiapu and Uawa catchments showing the extent of Cretaceous and Tertiary terrains, East Coast region, North Island, New Zealand (from Marden et al., 2008).
Earlier research on gullies has been in the form of local case studies (individual or clusters of gullies) and focussed primarily on the development of gullies over time and their contribution to sediment yield (De Rose et al., 1998; Betts et al., 2003; Marden et al., 2005). In these studies the volume of sediment removed from gullies was estimated using high-resolution digital elevation models (DEMs) constructed from aerial photographs to establish changes in elevation over time. These data were then used to derive a relationship between gully area and degradation rate for a limited range of gully sizes within Cretaceous terrain (De Rose et al., 1998; Marden et al., 2005) and Tertiary terrain (Betts and De Rose, 1999). These relationships were further investigated using the full complement of gully sizes within both terrain types and region-wide (Marden et al., 2008).

The early literature describing the ameliorating influence of restorative efforts, and in particular the time it takes to stabilise gullies under a forest regime, is in large part anecdotal (Allsop, 1973), seldom quantitative (Hicks, 1991; Phillips et al., 2000; Gomez et al., 2003), and has been evaluated only for small study areas within one (Cretaceous terrain) of the region’s two geologic terrains (De Rose et al., 1998; Marden et al., 2005). Only with the recently completed mapping of actively eroding gullies has the scale of the gully-erosion problem (i.e., location, number and size of treated and untreated gullies), within the Waipaoa (2,205 km²), Waiapu (1,749 km²) and Uawa (557 km²) catchments, become clearer both at a catchment and regional scale (Marden et al., 2008).

Anecdotally, gullies have been considered the largest contributor to the sediment load of rivers draining the three major catchments in the East Coast region (Page et al., 2001; Marden et al., 2005). This was later quantified and expressed as an equivalent contribution to their average annual suspended sediment yield (Marden et al., 2008).

In this paper, we present a summary of models developed using data from long-established forests planted for erosion control to establish the number of years required to stabilise reforested gullies, based on the measured reduction in ‘active’ gully area as a function of increasing tree canopy size, in two contrasting geologic terrains. A gully is considered to have stabilised successfully when the canopy has ‘closed’ and bare ground is no longer visible on aerial photographs. The models are then used to quantify sediment production derived from gullies of varying size within these terrains. An important application of this research has been to model the effectiveness of past reforestation efforts at catchment scale and use this to determine reforestation scenarios that would afford the greatest potential reductions in gully-derived sediment following treatment of remaining unplanted gullies.

**Background**

Based on written accounts of gully erosion in upper catchment areas, it is likely that gully initiation occurred within a decade or two following deforestation around the turn of the 19th century (~1880–1920) (Allsop, 1973; Gage and Black, 1979). There followed a period of geomorphic slope adjustment in response to the removal of this forest (Hill, 1895; Henderson and Ongley, 1920), supported by observations of increased channel aggradation (Kennedy, 1912; Laing-Meason, 1914), attributable predominantly to gully erosion (Gage and Black, 1979). Furthermore, the earliest available aerial photography (~1939–1957) show gully erosion to be absent from remaining steepland areas of indigenous forest, suggesting it had been minimal in forested areas subsequently cleared for pastoral use. Once initiated, gullies rapidly became entrenched, with steep
sides showing evidence of repeated slumping. Together with associated mass movement processes, the gullying is unique in that its magnitude is greater than in any other region of New Zealand and it is one of the most spectacular examples of its kind to be found anywhere in the world (NWASCO, 1970).

A combination of factors predisposes the East Coast region to gully erosion. These include tectonic influences (e.g., earthquakes, uplift rates), geologic influences (rock type, degree of faulting and crushing), a climate influenced by tropical cyclones, and the recent clearance of vegetation from steep slopes. New Zealand’s East Coast is on the circum-Pacific mobile belt at the boundary of the converging Pacific and Indian-Australian lithospheric plates, which results in high rates of tectonic uplift (1–7 mm/yr) and frequent large magnitude earthquakes (Smith and Berryman, 1986). The region can be subdivided into two geologic terrains based on lithology, age and style of deformation – in this paper we adopt the terms ‘Cretaceous terrain’ and ‘Tertiary terrain’. The inland, Cretaceous terrain comprises variably indurated, extensively sheared, alternating siliceous mudstone and sandstone of Late Cretaceous to Palaeocene age that is part of the East Coast Allochthon (Mazengarb and Speden, 2000). Eastward of this allochthon lies the autochthonous Tertiary terrain, comprising tectonically less-deformed, bedded to massive sandstones and mudstones of Early to Middle Miocene age (Fig. 1).

Initial on-farm attempts to control gully erosion were largely ineffective. The increasing costs of on-farm gully stabilisation to protect downstream infrastructure and utilities led the Government to purchase large tracts of eroding farmland in the headwaters of the Waipaoa, Uawa and Waiapu catchments for reforestation. Reforestation began in 1961, and by 1985 in excess of 40,000 hectares of exotic forest had been established. The principal tree species include radiata pine (\textit{Pinus radiata}), Douglas fir (\textit{Pseudosuga menziesii}), and assorted minor species. Beginning in the 1980s a second wave of forest plantings followed extensive damage to large tracts of pastoral hill country during successive storms in 1980 and 1982, and Cyclone Bola in 1988. As at consequence, a total of ~135,000 ha of eroding pastoral hill country had been replanted in exotic forest by 1997.

The regional climate is warm temperate maritime, with warm moist summers and cool wet winters. Rainfall gradients increase from south to north and from the coast to inland areas. Mean annual rainfall for coastal areas in the south (Gisborne City) is 1200 mm, while that in the north (Ruatoria Township) is 1600 mm. Inland areas in the south of the region receive ~2500 mm, while areas in the north and near the main divide of the Raukumara Range get 4000 mm (Hessell, 1980). The region’s climate is strongly influenced by the El Niño/Southern Oscillation (ENSO), with an increase in major rainfall events during La Niña conditions, and severe and prolonged droughts during El Niño years. Tropical cyclones during the summer months (November–March) have on occasion accelerated erosion; the last was in 1988 (Cyclone Bola) during which 300–900 mm of rain fell in a 5-day period. From the turn of the 20th century to 1995 there had been 29 extreme rainfall events in which the discharge of the Waipaoa River exceeded 1500 m$^3$ s$^{-1}$, and hillslope failure was widespread. In Waipaoa catchment there is a 29% chance of a major event every year, and a greater than 99% chance one will occur every 10 years (Kelliher et al., 1995). Erosion-generating storms and associated flooding in the Uawa and Waiapu catchments are more frequent and in the Waiapu catchment have a recurrence interval of between 2.6 years in the headwaters and 3.6 years near the coast (Hicks, 1995). This volatile climate contributes to high erosion rates (Water and Soil Directorate, 1987).
Methods

Model components
The development of models to establish the number of years required to achieve gully stabilisation following reforestation, and the rates of gully degradation, in order to assess the effectiveness of past reforestation efforts in reducing gully-derived sediment yield and to forecast potential reductions in sediment yield from as yet untreated gullies, are all founded on GIS-based data sets of the region-wide distribution of actively eroding gullies (Marden, unpublished). Gullies were mapped for two time periods for which aerial photographic coverage was available for the entire region. The earlier coverage was based on aerial photography flown between 1939 and 1957, but primarily in 1957. This captures the extent of gully development following clearance of the indigenous forest (~1880s to 1920s) until reforestation for erosion control began in 1961 (i.e., the pre-reforestation period). Later mapped coverage, based on aerial photography flown in 1997, captures the status of gully erosion after ~40 years of reforestation effort (i.e., the reforestation period).

Betts and De Rose (1999) defined gullies as areas of actively eroding bare ground that were contiguous with the channels that drained them; adjacent areas of broken ground attributable to mass-movement were excluded. Incipient gullies were not mapped because they were not considered to be active sediment sources. Gullies were identified stereoscopically from aerial photographs and their planimetric area scribed directly onto non-orthorectified photographic prints. This linework was then digitised and ortho-corrected using MAPVIEW. We refer to the GIS-based coverage of gullies by the date of photography used, that is, 1957 and 1997, respectively. For the period 1957–1997, changes in the total number and composite gully area, gully size distribution, and the frequency of gully sizes and their distribution relative to areas subsequently planted in exotic forest and to geological terrain were determined in ESRI Arc Map version 9.3. For reforested gullies, the planting date was obtained from forest stand records.

Gully stabilisation
The concept of gully stabilisation is based on the measured change in ‘active’ gully area between 1957 and 1997 as a function of increasing tree canopy size (resulting in a reduction in gully size) or conversely, gully reactivation (resulting in an increase in gully size), over the length of a rotation of exotic pines. This time-dependent model thus relies on the measurement of individual gullies before reforestation (~1957), knowledge of the date of planting and the duration (years) since planting, and the remeasurement of each gully area in 1997. For reforested gullies the year each gully was planted is known, thus this model is based on and is only applicable to gullies stabilised by planted exotic forest.

An earlier model depicting the number of years required to achieve stability in gullies following reforestation was developed using data for gullies located in a limited reforested area (140 km²) confined to Cretaceous terrain within the upper reaches of Waipaoa catchment (Marden et al., 2005). The current and improved model (Fig. 2) incorporates data from a greater number and size-range of gullies located within the entire exotic forest estate as of 1997 (1350 km²), a wider range of planting dates spanning a ~40-year reforestation period and it encompasses all forested gullies within both the Cretaceous and Tertiary terrains. During development of this model, the exploration of functions of log-transformed variables showed the probability of gully stabilisation is linearly related to area (size) and ‘number of years since planting’. For modelling, it was assumed that gully size had not appreciably increased between 1957 (Gully Area57 in Table 1) and the time of planting (year). Modelling also indicated
that for the ‘number of years since planting’, there is a slowing of the rate of stabilisation after about 1984 (see Discussion). To allow for this effect, ‘time since planting’ was modelled as two separate variables. The first variable denotes the number of years a gully had been planted up until 1984 (that is, those gullies planted during the first period of reforestation) or zero for gullies planted after 1984 (that is, those gullies planted during the second period of reforestation). The second variable denotes the number of years between

<table>
<thead>
<tr>
<th>Parametric model term</th>
<th>Estimate</th>
<th>Std Error</th>
<th>z value</th>
<th>Exp (Estimate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept (Cretaceous geology)</td>
<td>0.814</td>
<td>0.153</td>
<td>5.32</td>
<td>2.26</td>
</tr>
<tr>
<td>Log (Gully Area57) (Cretaceous geology)</td>
<td>-0.949</td>
<td>0.097</td>
<td>-9.75</td>
<td>0.387</td>
</tr>
<tr>
<td>Intercept difference (Tertiary–Cretaceous)</td>
<td>0.026</td>
<td>0.101</td>
<td>0.252</td>
<td>1.026</td>
</tr>
<tr>
<td>Log (Gully Area57) difference: (Tertiary–Cretaceous)</td>
<td>-0.281</td>
<td>0.122</td>
<td>-2.29</td>
<td>0.755</td>
</tr>
<tr>
<td>No. years after 1984, or zero</td>
<td>-0.034</td>
<td>0.012</td>
<td>2.94</td>
<td>0.966</td>
</tr>
<tr>
<td>No. years before 1984, or zero</td>
<td>0.145</td>
<td>0.019</td>
<td>7.56</td>
<td>1.155</td>
</tr>
</tbody>
</table>

Table 1 – Coefficients of the linear logistic model for estimating the probability of gullies stabilising

| Probability (expressed as log odds) of the closure of gullies on Cretaceous geology at Log (Gully Area57) = 0 |
| Effect of Log (Gully Area57) on Cretaceous geology. For every unit increase in Log (Gully Area57) there is a 0.949 decrease in logodds of closure (i.e. larger gullies have a smaller probability of closing) |
| Difference in intercepts between Tertiary and Cretaceous (Tertiary has a slightly higher logodds [0.814+0.026]), though non-significant probability of closure at Log (Gully Area57) = 0 |
| Difference in slopes between Tertiary and Cretaceous (Tertiary has a steeper negative slope than Cretaceous [-0.949 – 0.281] and this difference is significant). Tertiary gullies have a smaller chance of closing compared with Cretaceous gullies |
| Additional effect on the logodds of gully stability after 1984 |
| Additional effect on the logodds of gully stability if before 1984 |

Smooth curve: Cretaceous: 1.5 effective parameters, p-value = 0.5
Smooth curve: Tertiary: 1.5 effective parameters, p value = 0.04

Note: The exp (Estimate) column gives the amount by which a unit change in the model term would multiply the probability of a gully stabilising by 1997. For example, each additional year of planting before 1984 multiplied the probability of stabilising by 1997, by 1.155.
1984 and the last date of photography used in this analysis (1997) or zero for gullies planted before 1984 (Table 1).

The probability of gully stabilisation is thus given by a logistic regression function of the form:

\[ p = \frac{1}{1 + e^{-(a + b \ln(A) + cN)}} \]

where \( p \) is the probability of a gully stabilising (and is bounded between 0 and 1), \( A \) is log gully area \((\log_e)\) in hectares, \( N \) is either the number of years after planting (if before 1984) or the number of years between planting and 1997 (if after 1984), and \( a \), \( b \) and \( c \) are model coefficients. The Generalized Linear Model procedure in the R statistical computer environment (R Development Core Team, 2008) was used to derive coefficients (Table 2) for a binomial response function of the probability of gully stabilisation occurring by 1997 \((0 = \text{gully stabilised, } 1 = \text{gully remains active})\). Input parameters were planting date, geology, gully areas mapped in 1957 (i.e., before reforestation), and gully areas mapped in 1997. To improve the fit, a non-parametric curve was added to the model for each geological terrain (Wood, 2006) and simplified by minimising the Akaike Information Criterion (Akaike, 1974) (Fig. 2). This balances the information summarised in the model against the number of parameters.

The estimates of the resulting model for predicting probabilities from gully area, geology and year planted are shown in Table 1, while the predictions for chosen combinations of geology, gully area, and year planted are presented in Table 2.

### Table 2 – The probability of different-sized gullies stabilising following planting and the length of time (years) required for gullies associated with a) Cretaceous terrain and b) Tertiary terrain

<table>
<thead>
<tr>
<th>a) Cretaceous terrain</th>
<th>Years after planting</th>
<th>b) Tertiary terrain</th>
<th>Years after planting</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gully size (ha)</strong></td>
<td><strong>10 years</strong></td>
<td><strong>20 years</strong></td>
<td><strong>30 years</strong></td>
</tr>
<tr>
<td>0.1</td>
<td>0.93</td>
<td>0.98</td>
<td>0.99</td>
</tr>
<tr>
<td>0.5</td>
<td>0.81</td>
<td>0.93</td>
<td>0.98</td>
</tr>
<tr>
<td>1.0</td>
<td>0.70</td>
<td>0.88</td>
<td>0.97</td>
</tr>
<tr>
<td>5.0</td>
<td>0.29</td>
<td>0.56</td>
<td>0.84</td>
</tr>
<tr>
<td>10.0</td>
<td>0.16</td>
<td>0.36</td>
<td>0.71</td>
</tr>
</tbody>
</table>

### Gully degradation and sediment yield

Previous studies have estimated the volume of sediment removed from gullies on the basis of elevation differences using high-resolution digital elevation models (DEMs) constructed from sequential aerial photography (De Rose et al., 1998; Betts and De Rose; 1999, Marden et al., 2005, 2008). For the wider range of gully sizes analysed (0.07–60.5 ha) by Marden et al. (2008), changes in gully depth were derived by subtracting the DEM representing the end of a measurement period (1997) from the DEM representing the beginning of a measurement period (1957). The values in the “difference image” within each gully boundary were then averaged and divided by the duration of the measurement period (in years) to derive an
average annual increase in depth (m/year). Multiplying this by the gully area gives the degradation rate (m³/year) for each gully. Correlation between observations of the same gully at different times and of different gullies at the same site were accommodated by fitting the model

\[
\text{Rate}_{ijk} = a_G + b_G \sqrt{\text{Area}_{ijk}} + s_i + g_{ij} + e_{ijk},
\]

where \(e_{ijk}\) are random differences between time periods at one gully, \(g_{ij}\) are random differences amongst gullies at the same site, and \(s_i\) are random differences between sites. The data indicated the constant \(a_G\) and slope \(b_G\) differed between terrain types and so separate lines were fitted for each (Fig. 3). Analysis used the nlme package (Pinheiro et al., 2008) within the statistical computing language R (R Development Core Team, 2008).

Irrespective of land cover, all calculations of sediment production assume that gullies produced sediment at a rate proportional to their area and that area changed linearly between 1957 and 1997. We adopt this simplistic assumption based on observations from sixty-six DEMs from 37 gullies located at six sites. We concluded that the combination of other potentially influential site factors, including slope length, steepness and aspect, type of geomorphic process (weathering, slumping) and degree of surface dissection (rilling) within each gully is complex, highly variable and seemingly unique. Further work is required to better understand the specific processes governing gully growth.

To calculate sediment production from gullies that did not exist in 1957 but were present in 1997 (i.e., their exact date of initiation is unknown) we assumed, on the basis of their small size as of 1997, that they had been sites of active sediment generation for no longer than half the duration of the 1957 to 1997 measurement period (i.e., ~20 years). Similarly, the calculations for gullies present in 1957 but ‘closed’ by 1997 (predominantly due to reforestation but exact date of closure unknown), we assume that these gullies had generated sediment for no longer than half the duration of this 40-year measurement period. These assumptions are based on previous research showing that for the majority of gully sizes represented, reforestation effectively closes them down within 20 years of planting (Marden et al., 2005). We adopt the annual suspended sediment yields of Hicks and Shankar (2003) for the Waipaoa (15 Mt/year), Waipu (35 Mt/year) and Uawa (5 Mt/year) rivers as being representative of the reforestation period (post-1960) and calculate sediment production from gullies as a proportional (%) equivalent of the annual suspended sediment yield of these rivers. The mass (Mt) of material supplied by gully erosion was computed using a dry bulk density of 2000 kg/m³ (Phillips, 1988; Marden et al., 2005; cf. De Rose et al., 1998). The estimates represent an upper bound because no account is taken of deposition in feeder channels and on fans, or of the proportion of coarse sediment (gravel) generated by gully erosion (Gomez et al., 2003).

### Gully initiation

A model that takes into account sediment yield derived from ‘new’ gullies that were not evident at the beginning of the measurement period (1957) but were present in 1997, a 33% increase (Marden et al., 2005, 2008), was developed by Herzig et al. (submitted). New gullies were evenly distributed throughout the measurement period.

\[
fr = 0.33 / 41 \times \text{duration}
\]

\[
ng = \text{init} \times (1 + fr)
\]

\(fr\): proportion of new gullies
\(ng\): number of new gullies
\(duration\): length of modelling period (years)
\(init\): number of gullies at beginning of modelling period
As with the gully stabilisation model, this model does not take account of those gullies initiated sometime after 1957 but which had stabilised before 1997.

**Gully growth**

Unforested gullies increase in size (area) over time (Marden et al., 2005, 2008). To compare sediment yields generated from reforested gullies with that from as yet unforested gullies, Herzig et al. (submitted) developed a linear growth model for the latter based on the relationship between growth in gully length and size during the modelling period.

\[
A_{t+1} = A_t \left(1 + \frac{p}{100}\right)^2
\]

- \(A_{t+1}\): gully size at year \(t+1\)
- \(A_t\): gully size at year \(t\)
- \(p\): annual growth of gully length [%] (here \(p = 0.5\))

**Modelling gully-derived sediment yields for future reforestation scenarios**

Based on the gully stabilisation models (Marden et al., 2005, this paper) and the degradation model presented in Marden et al. (2008), additional models have been developed by Herzig et al. (submitted) specifically to forecast potential reductions in sediment yields from remaining untreated gullies, including those already considered too large to stabilise through reforestation. Several practical reforestation scenarios were considered (see Table 2 in Herzig et al., submitted). We present the scenario with the greatest potential for reducing gully-derived sediment yield. This requires the reforestation of all remaining untreated gullies by 2020. In addition, two sub-scenarios were modelled and compared (Herzig et al., submitted): (a) new gullies initiate during the modelling period (see section on Gully initiation) and remain untreated and (b) no new gullies initiate during the modelling period.

**Results**

**Gully stabilisation**

The logistic model shows that the probability of gullies stabilising following planting with exotic pines was strongly associated with gully size and the number of years since planting, and for gullies of equivalent size, the duration since planting is similar in both geological terrains (Table 1). However, for those gullies within the Cretaceous terrain, each additional hectare in size multiplied the probability of stabilising by 0.387, compared with 0.292 for gullies in areas of Tertiary terrain. For example, a doubling of the area of a gully in Cretaceous terrain decreases the probability of it stabilising by a factor of \(0.387 \log (2) = 0.52\), whereas the doubling of the size of a gully located in Tertiary terrain decreases the probability by \((0.387 \times 0.755) \log (2) = 0.43\). It is to be expected that some time will elapse before trees become effective in stabilising a gully. The model estimates that for a gully planted for more than 13 years, the probability of achieving gully stabilisation, irrespective of lithology or initial gully size, increased by a factor of \(1.155^{10} = 4.2\) for any 10-year period. For gullies with a medium probability of stabilising, e.g., 0.5, a further 10 years of tree growth will increase this probability to 0.82, a significant increase. In contrast, a gully with a high probability of stabilising, e.g., 0.9, will increase to just 0.98 over a similar time frame. Irrespective of geological terrain, for gullies of 1 ha and less at the time of planting, the greatest gains in the probability of gullies stabilising are within the first 10 years after planting (Table 2). The model also predicts that for 5–10-ha gullies located in areas of Cretaceous terrain and for 5-ha gullies in Tertiary terrain the same level of probability-of-stabilising will not be attained until 30 years after planting. For gullies ~10 ha in size in areas of Tertiary terrain this will take longer than 30 years (Table 2).

For gullies ~1.0 ha and less, ~90% of those planted for 20 years stabilised, as did almost all gullies planted for 30 years (Fig. 2). In contrast, for 5-ha gullies, ~60%...
of those planted for 20 years stabilised and 90% of those planted for more than 30 years stabilised. For gullies larger than 10 ha, the model predicts that the proportion stabilising 20 years after planting lies between 20 and 36% and the proportion stabilising after 30 years lies between 51 and 71%.

Analysis of the gullies present in 1957 and subsequently planted in exotic forest resulted in a 28% reduction in total gully area; however, 385 remained active, of which ~50% had halved in size, while none of the gullies larger than 20 ha had stabilised within 30 years of planting and few had reduced in size by as much as half.

Gully degradation
Within the Tertiary terrain there was no evidence (p = 0.4) that the rate of increase in gully depth varied with gully area (Fig. 3).

\[
\text{Rate} = 0.1963 + 0.0117 \sqrt{\text{Area}} \quad \text{se} = 0.118
\]

% Variance explained = 19%

The rate was therefore taken to be a constant 0.242 m/year (se = 0.131) regardless of area. However, within the Cretaceous terrain there was strong evidence of a relationship (p= 0.002)

\[
\text{Rate} = 0.0558 + 0.09526 \sqrt{\text{Area}} \quad \text{se} = 0.123
\]

% Variance explained = 61%

which was therefore used to estimate total degradation.

Sediment production
Overall, the rate of sediment production from gullies reforested during the period 1957–1997 (calculated using total reforested area) in the Waiapu catchment (9402 t/km²/year) was similar to that in the Waipaoa catchment (8370 t/km²/year), but considerably greater than in the Uawa catchment (5641 t/km²/year) (Table 3).

By terrain, reforested gullies in Cretaceous terrain generated the greatest proportion of the total sediment yield derived from both terrains combined: 51% in Waipaoa, 77% in Waiapu and 92% in Uawa catchment. Also, during the measurement period reforested gullies in both terrains collectively contributed 55%, 23% and 54% of the total gully sediment yield generated across all

![Figure 2](image-url) – Predicted probabilities of a gully stabilising in response to reforestation plotted against years since planting for 0.1-ha, 1-ha, 5-ha, 10-ha and 20-ha-sized gullies within Cretaceous and Tertiary terrains.
Figure 3 – Relationship between rate of increase in gully depth (m/year) and the square root of gully area for individual gullies located in Cretaceous (n = 21 observations) and Tertiary (n = 45 observations) terrains (from Marden et al., 2008).

Table 3 – Comparative sediment yield (Mt/year⁻¹) and annual rates (t/km²/year) for gullies reforested with exotic pines during the period 1957 to 1997. Calculations of mass per square kilometre for reforested areas are based on the area of each terrain planted in exotic forest at the end of the measurement period.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Waipaoa</th>
<th>Waipu</th>
<th>Uawa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#Mt/year⁻¹</td>
<td>t/km²/year</td>
<td>Mt/year⁻¹</td>
</tr>
<tr>
<td>Reforested gullies – Tertiary terrain</td>
<td>1.85</td>
<td>5,331</td>
<td>0.75</td>
</tr>
<tr>
<td>Reforested gullies – Cretaceous terrain</td>
<td>1.95</td>
<td>18,224</td>
<td>2.5</td>
</tr>
<tr>
<td>Total for reforested gullies</td>
<td>3.8</td>
<td>8,370</td>
<td>3.3</td>
</tr>
<tr>
<td>Percent of catchment total</td>
<td>55%</td>
<td></td>
<td>23%</td>
</tr>
<tr>
<td>Catchment total (all land uses)</td>
<td>6.65</td>
<td></td>
<td>14.2</td>
</tr>
<tr>
<td>Average annual suspended sediment yield (ssy)</td>
<td>15</td>
<td></td>
<td>35</td>
</tr>
<tr>
<td>Equivalent contribution (%) to ssy from reforested gullies</td>
<td>25</td>
<td></td>
<td>9</td>
</tr>
</tbody>
</table>

# assumptions behind calculation are explained under Gully degradation and sediment yield
land uses, which is equivalent to 25% (3.8 Mt/year), 9% (3.3 Mt/year) and 25% (1.25 Mt/year) of the average annual suspended sediment load of the Waipaoa, Waiapu and Uawa rivers, respectively (Table 3).

**Effectiveness of past reforestation in reducing gully-derived sediment**

At catchment scale, the magnitude in the reduction in gully-derived sediment yield during the measurement period (1957–1997) reflects the timing and the area of land reforested. In the Waipaoa catchment, the early establishment of exotic forest in the most gully-prone part of this catchment resulted in a 33% decrease in gully-derived sediment yield. By comparison, where the early planting of exotic forest was less extensive (Waiapu catchment) or more recent (Uawa catchment), past reforestation has been effective in reducing sediment yield by 16% and 20% respectively, and relative to yields had there been no reforestation undertaken within these catchments (Herzig et al., submitted).

Region-wide, the total annual yield derived from gullies for all catchments combined, as of 2008, is approximately 22% less than if gullies had remained unforested for the duration of the measurement period (Herzig et al., submitted).

**Effectiveness of future plantings**

Results show that at catchment scale, gully-derived sediment yield in each of the three major catchments could be halved by 2030 and remain constant thereafter if all remaining untreated gullies were reforested before 2020 and any new gullies initiated were also reforested. (Fig. 4).

The greatest number of untreated gullies occurs in the Waiapu catchment, where it is
expected that by the end of the modelling period sediment yield would decline to ~11Mt/year (Fig. 4) if no new gullies initiate from 2008–2050. Conversely, if new gullies were formed but remained untreated during this period, the annual sediment yield as of 2050 would be approximately twice that if no new gullies were initiated (Herzig et al., submitted).

Discussion
Gully erosion in the headwater reaches of the Waipaoa, Waiapu and Uawa catchments was initiated within a few decades of the clearance of indigenous forest for pasture (Allsop, 1973; Gage and Black, 1979), and in the absence of a forest cover an increase in gully depth with gully size is commensurate with greater runoff rates and enhanced runoff concentrations. While previous research of localised gullies has linked gully initiation to extreme storm events (Betts et al., 2003; Parkner et al., 2007) clear magnitude-frequency relationships with gully growth have yet to be quantified, particularly at regional scale. In addition to storm events, gully growth also relates to intrinsic gully dynamics (Fuller and Marden, 2011). Within Tertiary terrain the relationship between the rate and mode of gully expansion, which is predominantly by fluvial processes, is weak (Fig. 3). These gullies therefore deepen with little corresponding increase in gully area, and thus typically maintain a linear shape. In contrast, following initial channel incision, gullies associated with structurally weak materials typically found in areas of Cretaceous terrain increase in size more by mass movement than by fluvial processes and increasingly become amphitheatre-shaped. For such gullies, the rate of increase in depth increases with size (area) and thus this relationship is stronger (De Rose et al., 1998; Betts and De Rose, 1999; Marden et al., 2005, 2008).

Gullies do not all form at the same time or develop at the same rate. Phases of gully expansion are invariably followed by periods of inactivity and furthermore the response time required to stabilise a gully following reforestation is highly variable. From the gully stabilisation model, gully area (size) at the time of planting is the most important factor that determines the length of time required to achieve stabilisation. Whatever the initial size of a gully, the probability of it stabilising is improved by planting and the length of time since planting (Fig. 2). However, the model identified a slowing of the probability of stabilisation for gullies planted after 1984. This reflects a hiatus in reforestation efforts between the early plantings (1960–1985) and the start of a second replanting period about 1992 (i.e., post-Cyclone Bola), only 5 years before the remeasurement of gully area in 1997 and before canopy closure had occurred. Any reduction in gully planimetric area over time is attributed to the progressive closure of the canopy. In this region, canopy closure occurs ~8–10 years after planting (Marden and Rowan, 1993) and so only the smallest of gullies planted during the 1992–1997 reforestation period would have stabilised, while larger gullies would have shown only partial canopy closure and thus partial stabilisation. A mature, closed-canopy stand of Pinus radiata has the potential to reduce runoff by between 25 and 30% (Pearce et al., 1987), thereby influencing the hydrology of gullies and hence erosion activity within, them. Thus, for all but the largest and most active gullies, reforestation is most effective when the entire drainage basin surrounding individual gullies is planted (Marden et al., 2005) and the roots of closely planted trees increase the stability of gully side-slopes (Dolman, 1982).

Analysis of the probability of gully stabilisation indicates that lithologic terrain has little influence on the pattern of stabilisation for small gullies; however, there is strong evidence that as gully size increases, those located in areas of Tertiary terrain are
less likely to stabilise in response to reforestation than similar-sized gullies located within Cretaceous terrain. While the difference for 1-ha gullies in either terrain is negligible, the probability of a 10-ha gully stabilising in Tertiary terrain is almost half that of a similar-sized gully in Cretaceous terrain. This is because the primarily fluvial-dissected gullies in Tertiary terrain are generally steep-sided and devoid of soil in which to plant, hence a significant proportion of these gullies remain devoid of vegetation for longer. In contrast, a characteristic feature of the sidewalls of many of the larger gullies in areas of Cretaceous terrain is the occurrence of mass movement, principally slumping. Here, slopes are less steep, their soil mantle is largely intact, and a larger proportion of the gully side-slopes are accessible to planters. Thus plants can be established over a larger area of the gully, and plant survival and growth are enhanced by the presence of a soil mantle, resulting in earlier canopy closure. In this region, and for the majority of gullies, there are no other site variables that could be considered as significant impediments to growth for this species of pine.

The findings of an earlier model of predicted probabilities and duration (years after planting) required to stabilise 1- and 5-ha gullies in areas of Cretaceous terrain (Fig. 6 in Marden et al., 2005) are similar to those predicted using the current model (Fig. 2). However, in the current model, the addition of predicted probabilities for 10- and 20-ha gullies has highlighted the long time-frame required to stabilise these larger-sized features, particularly in areas of Tertiary terrain. Thus the larger the gully before planting, the lower the probability treatment will succeed. Conversely, the smaller the gully at the time of planting, the higher the probability treatment will succeed. Furthermore, for the largest gullies, reforestation is unlikely to be effective within the duration of one forest rotation, though in most instances partial stabilisation will likely occur.

Sediment yields from gullies vary considerably through time (De Rose et al., 1998; Betts and De Rose 1999; Marden et al., 2005, 2008), decreasing as the number of years since planting increases (Marden et al., 2005). The early reforestation of gullies in headwater catchments within Cretaceous terrain (1960s to 1980s) proved most successful, particularly in Waipaoa catchment (Phillips et al., 1991; Marden and Rowan, 1993; Gomez et al., 2003; Marden 2004; Marden et al., 2005). Within this terrain, the majority of gullies progressively stabilised and sediment production from them declined within a decade or two of planting (Gomez et al., 2003; Marden et al., 2005). From the gully stabilisation model (Fig. 2) it can be inferred that, as gullies stabilise, sediment yield from 90% of gullies ~0.5 ha in size and 60% of 5-ha gullies will be negligible within 20 years of planting. Within 30 years, 90% of 5-ha gullies will no longer be significant point sources of sediment and gullies larger than 10 ha will diminish in size and activity but probably remain a point source of sediment well into the second forest rotation. For these medium-sized gullies to stabilise successfully, adjacent areas of associated mass movement and likely part or all of their surrounding watershed would require reforestation. Remaining gullies that were already too large at the time of planting (>20 ha) will show little response to reforestation and likely increase in activity and size, thus sediment yields will remain high.

Between 1957 and 1997 ~135,000 ha of formerly eroding pastoral hill country were reforested, primarily for erosion control. Physical evidence that reforestation has been effective in stabilising gullies include channel narrowing and incision as an initial response to the decrease in sediment yield. A similar response to reforestation has been widely documented, notably in
Europe where major reforestation occurred a century ago (Piégay and Salvador, 1997; García-Ruiz et al., 1997; Liebault and Piégay, 2001; Surian and Rinaldi, 2003). Additional indicators are the survival of forest plantings to increasingly form a closed canopy within a once-active and open gully, channel incision into depositional fans emanating from them, and the subsequent stabilisation of these fans (see Fig. 7 in Marden et al., 2005). The steepness of gully channels and their direct connectivity to a permanent stream precludes the possibility that sediment trapping and infilling of the gully channel would in itself result in gully stabilisation. Sediment storage within linear gully channels is minimal and in the largest of the gullies is less than 20% of the sediment generated (from De Rose et al., 1998) and probably as low as 5% (Marden et al., in prep).

Since Cyclone Bola (1988), the area planted in exotic forest has more than doubled. Previous research has shown that there has been a significant reduction in gully-derived sediment in response to reforestation at a local scale (De Rose et al., 1998; Marden et al., 2005). Sediment yield at catchment scale declined significantly over the ~40-year modelling period where reforestation of gullies was extensive and early (e.g., Waipaoa catchment). Reforestation, however, has been less effective in reducing sediment yield in other catchments where the early forest planting was less extensive (e.g., Waipu catchment) and where the reforestation of gully-prone terrain has been more recent (e.g., Uawa catchment). Irrespective of declining sediment yields, the generation of sediment from reforested gullies at catchment scale remains high, with the greatest proportion derived from gullies in Cretaceous terrain – 51% in Waipaoa, 77% in Waipu and 92% in Uawa catchment (from Table 3). This is because large and essentially ‘unreliable’ gullies located within reforested terrain remain as significant point sources of sediment, and increasingly, and as an artefact of more recent changes in land use, significant areas of erosion-prone hill country have been retired from pastoral farming for conversion to exotic forest.

Modelling suggests that the most effective strategy for reducing sediment yield in each of the three catchments would involve the planting of all remaining untreated gullies, and that the earlier the planting the greater and sooner the reduction in sediment yield. At catchment scale, gully-derived sediment yield in each of the three major catchments could be halved by 2030 and remain constant thereafter if all remaining untreated gullies were reforested before 2020 and no new gullies were initiated during this period. Conversely, if the reforestation of these remaining gullies and any newly initiated gullies were not treated, the annual sediment yield by 2050 would be twice as high as if there were no newly initiating gullies.

At catchment scale, any appreciable decline in gully-derived sediment yield will likely take ~40 years. Previous research has shown that other potential environmental benefits, including improved water clarity and quality (Parkyn et al., 2006) and a reduction in channel aggradation and flood risk (Gomez et al., 2003) will likely accrue following the reforestation of remaining gullies. In the longer term, the region will benefit financially through a reduction in the incidence and costs associated with repairing damaged regional infrastructure, particularly bridges and roads.

Conclusions
Past reforestation has been successful in stabilising actively eroding gullies. Gully area (size) at the time of planting is the most important factor determining the probability and number of years required to achieve stabilisation. Lithologic terrain has little influence on the timing of stabilisation for
small gullies. However, as gully size increases those located in areas of Tertiary terrain will require longer to stabilise than similar-sized gullies located within Cretaceous terrain. Reforestation of gullies, inclusive of areas of associated mass movement within their watershed, is the most practical and effective means of stabilising all but the largest gullies and it is achievable within one forest rotation (~27 years).

Although gullies occupy only a small percentage of hill country areas and, notwithstanding the considerable area reforested to control erosion, gullying remains the most significant sediment-producing process in each of the three major river systems in the East Coast region.

At catchment scale, gully-derived sediment yield in each of the three major catchments could be halved by 2030 and remain constant thereafter if all remaining untreated gullies were reforested before 2020 and no new gullies were initiated during this period.

The models developed here would be suitable for use in similar gully-prone hill country areas elsewhere in the North Island where reforestation with exotic pines is likely to be a primary method for controlling gully erosion. These models are, however, likely to be less applicable in other geologic terrains where the geomorphic processes that govern gully development are different.

Acknowledgements
This work was supported by the Foundation for Research Science and Technology, contract number CO9X0706. We are indebted to the Gisborne District Council and in particular to the staff of the Soil Conservation Section for providing access to their collection of aerial photography. The assistance of the Ministry of Agriculture and Forestry (East Coast Forestry Project, Gisborne Office) in providing GIS and financial support is gratefully acknowledged. Nic Faville assisted with the figures, Anne Austin edited the text, and Mandy Cains formatted the draft manuscript.

References


