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Effectiveness of vegetative mitigation strategies in the restoration of fluvial and fluvio-mass movement gully complexes over 60 years, East Coast region, North Island, New Zealand

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Abstract

Background: Early (1957–1997) remediation strategies, predominantly *Pinus radiata* D.Don afforestation and indigenous shrubland reversion, proved effective in treating gully erosion in the East Coast region, North Island, New Zealand. However, the expansion of untreated gullies and initiation of new ones necessitated additional investment in land-use change (1997–2017) to reduce their on- and off-site impacts.

Methods: Gullies were digitised from aerial photography flown in ~1957 (before reforestation) and again in 1997. The region was re-flown in 2017, providing an opportunity to assess remediation successes and failures. For hill country areas, gully location and size were recorded by vegetation type, for major catchments, for two contrasting geological terrains, and for land designated in Gisborne District Council's Combined Regional and District Plan as Land Overlay 3A (LO3A).

Results: Between 1997 and 2017, 601 treated gullies fully re-stabilised and 315 new gullies formed. There remain 1864 gullies, comprising 5347 ha. This represents a 13% reduction in numbers and a 31% decrease in area during this 20-year period. Over the longer 60-year period, and across all land uses, 2942 treated gullies successfully stabilised. However, with the initiation of 1446 new gullies there are currently 5347 ha of gully requiring further treatment, with the largest of the affected area equally distributed across pastoral and reforested hill country and primarily located within the Tertiary terrain, Waiapu catchment, and areas designated as LO3A.

Conclusions: Although attempts at gully remediation since the early 1960s have resulted in a 45% reduction in gully number, the current area of hill country affected by gullying is only 5% less than 60 years ago. During this period, gully initiation and development have outstripped mandated erosion control targets set by the East Coast Forestry Project (ECFP), for land designated as LO3A, and for the 'Restoration of the Waiapu Catchment' by 2020-22. Addressing ongoing on- and off-site impacts of gully erosion will require further significant long-term investment in the prioritisation and completion of these unfulfilled targets. For gullies identified in the National Environmental Standard for Plantation Forestry (NES-PF) as high erosion risk (orange zone) or where the erosion risk is very high (red zone), we recommend: (i) a revision of remediation strategies for the larger and more actively eroding of gullies destined for future afforestation, and (ii) for gullies within exotic production forests, the replanting of species (exotic or indigenous) better suited to providing long-term stabilisation, post-harvest.

Keywords: spatial-temporal changes in gully distribution; funded remediation strategies; successes and failures.

Introduction

Across many parts of the world gully erosion has been commonly linked with the degradation or modification of vegetation cover (Lyell 1849; Graf 1979; Prosser & Slade 1994; Prosser & Soufi 1998). In the East Coast region of the North Island, New Zealand (Fig. 1), the onset of gullying followed a period (~1880–1920) of forest removal from steep, headwater reaches of major catchments during which large tracts of virgin indigenous forest were felled for timber and the land converted to pasture (Marden et al. 2008, 2011, 2012, 2014, 2018; Herzig et al. 2011). By the early 1900s there were obvious signs that the landscape was adjusting to the removal of the indigenous forest cover (Hill 1895; Henderson & Ongley 1920), the most noticeable being the initiation of gully erosion. Once initiated, gully erosion escalated, exacerbated by major storms in 1938 and 1948, followed by a succession of heavy rainfall events in the late 1950s and early 1960s (Marden et al. 2008, 2012, 2018; Fuller et al. 2010, 2020).

The off-site impacts of increasing volumes of gully-derived sediment exceed that of any other region of New Zealand and include: (i) catastrophic aggradation within drainage channels (Kennedy 1912; Laing-Meason 1914), leading to the inundation of low-lying, highly productive alluvial terraces; (ii) an increased incidence of braid-channel widening and avulsion, bank erosion, and flooding downstream of gullied catchments (Hamilton & Kelman 1952; Gage & Black 1979); (iii) damage to personal property and regional infrastructure (Krausse et al. 2001); (iv) increasing difficulties associated with the management of constantly changing river systems (Leenman & Tunnicliffe 2018); and (v) elevated levels of suspended sediment (Hicks & Shankar 2003), affecting freshwater (Parkyn et al. 2006), and both near-and off-shore marine ecosystems. Over time, the effects of environmental degradation of the landscape have been detrimental to the wellbeing of local communities and have contributed to the low-socio-economic profile of the area (Ministry for Primary Industries 2014).

Early attempts at stabilising gullies using traditional on-farm soil conservation plantings of *Populus* (poplar) and *Salix* (willow) species, in conjunction with the construction of debris retention structures to stabilise side slopes and reduce channel scour (Dolman 1982), proved unsuccessful. In many instances the ongoing costs of controlling erosion exceeded the value of pastoral production (National Water and Soil Conservation Organisation [NWASCO] 1970). Due largely to the severity and extent of gullies present at that time, plantation-afforestation was considered a better land-use option and beginning in ~1960, and through to ~1985, the then New Zealand Forest Service planted ~35 000 ha of severely eroding pastoral land. The preferred species were exotic to New Zealand and included radiata pine (*Pinus radiata* D.Don), Douglas fir (*Pseudosuga menziesii* (Mirb). Franco), and an assortment of minor species, including *Pinus nigra* (Arn. Subsp. Laricio (Poir.) Maire), eucalyptus spp., and Australian blackwood (*Acacia melanoxylon* (R.Br). These early attempts at reforestation ultimately proved to be a practical, inexpensive, and successful treatment in slowing the rate of sediment production (NWASCO 1970) across much of the severely eroding hill country in this region (Phillips et al. 1991; Marden & Rowan 1993; Marden 2004; Phillips & Marden 2005, Marden et al. 2005, 2008, 2011, 2012, 2014, 2018). In a depressed regional economy, however, land-use change was slow (Parliamentary Commissioner for the Environment 1994), and pastoralism continued to dominate the landscape into the 1980s. A succession of storms, particularly Cyclone Bola (1988), caused significant erosion regionwide including the initiation and development of numerous new gullies. Direct government relief payments totalled NZ$111 million and private losses and expenditure may have been equally high (Parliamentary Commissioner for the Environment 1994).

Post-Cyclone Bola erosion control policies

In 1992, and in recognition of the vulnerability of this region to future storm-related damage, the government introduced the 'East Coast Forestry Project' (ECFP), the primary goal of which was to subsidise the establishment of 200 000 ha of 'protection forests' at a rate of 7000 ha/year over a 28-year period (1992–2020). With an overriding aim to bring about sustainable land use[1] the annual budget was set at NZ$6.5 million (Ministry of Agriculture and Forestry 1993). In 1998, following a review of the project's multiple environmental, social, economic, and employment goals, the project's focus was narrowed to a single objective. The primary aim was to achieve "sustainable land management on 60 000 hectares of severely erosion-prone land (target land) in the Gisborne District by 2020, by changing current land use". Further, "The Project will do this in any cost-effective way, including planting with radiata pine or other species, gully planting through soil conservation measures (e.g., pole planting and small-scale debris retention structures), and actively managing the reversion of pastoral land to indigenous scrub/forest".

Other key decisions were that Crown funding could be used for "gully planting, either within gullies or along the margins of other afforestation projects or without having to plant the surrounding land (in general this means the land can still be farmed)", and that "Gisborne District Council demonstrate commitment to introduce regulatory controls to address severe erosion" (Ministry of Agriculture and Forestry 2005). From 2009, Section 6:10 of the Gisborne District Council's Combined Regional and District Plan required all landowners with eroding land identified as Land Overlay 3A (LO3A) comprising ~50 000 ha of the worst of the worst eroding land use capability classes (NWASCO 1976) to have an effective tree cover or be fenced for reversion by 2021. In 2014 the Crown signed a high-level Relationship Accord with Ngāti Porou, and Gisborne District Council to support erosion control initiatives within Waiapu Catchment ('Restoring the Waiapu Catchment'). This accord aimed to accelerate the completion of works plans that included the treatment of ~23 000 ha (~46% of the regional total of severely eroded land designated as LO3A), and thereafter maintain an effective tree cover (Ministry for Primary Industries 2014).

Whether forest establishment was by private investment partnerships (mainly on low-erosion-risk pastoral hill country) or on target land funded through the ECFP, ~100 000 ha of new exotic forest was planted, primarily between ~1992 & 1997. Since 1997 an additional ~20 000 ha of exotic forest has been planted, bringing the total estate within this region to ~155 000 ha (Forest Owners Association & Ministry for Primary Industries 2016), ~22% of the region's hill country. In addition, since the year 2000, the funding of areas of advanced and/or emerging indigenous shrubland reversion, in combination with the planting of mānuka (*Leptospermum scoparium* J.R.Forest & G.Forst) with the potential to stabilise gullies, has been completed on ~4000 ha of marginal hill country (Ministry of Agriculture and Forestry 2000).

In this paper we evaluate the effectiveness of attempts to remediate gully erosion over the last 20-year (1997–2017) period and review successes and failures since gully remediation began 60 years ago (1957–2017). We present our findings in the context of the scope and scale of future remediation efforts required to minimise the initiation of new gullies, the treatment of existing gullies and the requirement for strategies better suited to preventing the re-activation of gullies located within existing areas of exotic production forests, after forest removal.

Methods

Study area

New Zealand's North Island East Coast region (8391 km^2) consists of three major catchments, the Waipaoa (2208 km^2), Ūawa (560 km^2), and Waiapu (1758 km^2) (Fig. 1), and 12 smaller catchments (3865 km^2). With >90% of the region classed as steep hill country, much of which is highly erodible (NWASCO 1970), these steepland rivers combined contribute on average ~55 Mt of suspended sediment annually (Hicks & Shankar 2003). This equates to ~33% of the total annual suspended sediment load of all New Zealand rivers combined but generated from only 2.5% of its land area (Hicks et al. 2011). Additionally, gullies alone contribute more than half the suspended sediment yield of each of the major East Coast catchments (Marden et al. 2005, 2008; Page et al. 2008).

A combination of factors pre-dispose the East Coast Region to gully erosion. These include tectonism (e.g., frequent earthquakes, high uplift rates), its geology (rock type, degree of faulting and crushing), a dynamic climate with frequent and often localised high-intensity rainfall events and an occasional subtropical cyclone, and the recent clearance of indigenous forest from steep slopes for conversion to pasture. The region can be subdivided into two geological terrains (*sensu* Von Zittel 1901) (Fig. 1) within which differences in lithology, age, and style of deformation of the bedrock have a strong influence on gully development. Comprising part of the East Coast Allochthon (Mazengarb & Speden 2000), an inland terrain consists of variably indurated, extensively sheared, alternating siliceous mudstone and sandstone of late Cretaceous to Palaeocene age, hereafter referred to as the Cretaceous terrain (2685 km^2, 32% of the region). Here, extensive tectonic shearing has predisposed the bedrock to mass movement (e.g., debris flows, deep-seated rotational slump, and shallow landslides) (Gage & Black 1979; Parkner et al. 2007). Mass movements reactivated by fluvial incision result in slope undercutting that often coincides with high-magnitude rainstorms (Fuller & Marden 2008). This combination of processes has led to the development of large (>10 ha) amphitheatre-shaped gullies, whose width exceeds their length (De Rose et al. 1998; Leenman & Tunnicliffe 2018; Taylor et al. 2018). The terms 'gully mass movement complex' (Pearce et al., 1987), 'fluvio-mass movement gully complexes' (*sensu* Betts et al. 2003), 'gully complex' (Parkner et al. 2007), and 'badass' gullies (Marden et al. 2018, Fuller et al. 2020) recognise the importance of deep-seated mass movement in gully development, and the large volume of sediment per land area they generate (De Rose et al. 1998; Gomez et al. 2003; Marden et al. 2008, 2014, 2018; Leenman & Tunnicliffe 2018). Also that they do not conform to any existing gully erosion or evolution model (Bergonse & Reis 2011).

Eastward of this allochthon lies an autochthonous terrain comprising tectonically less-deformed beds of massive sandstones and mudstones of early to middle Miocene age (Mazengarb & Speden 2000), hereafter referred to as the Tertiary terrain (5706 km^2, 68% of the region). Here, the mode and rate of development of linear gullies (length exceeds width) is predominantly by fluvial incision and is confined to incipient drainage lines (e.g., Schumm et al. 1984; Bocco 1991). The development of these gullies is strongly influenced by structural and lithological controls (Parkner et al. 2006, 2007) and their growth is by headward extension, with little corresponding increase in gully width (Marden et al. 2008).

Throughout this paper we use the shortened terms 'gully' and/or 'gullies', prefaced by either 'linear' or 'amphitheatre-shaped'.

The regional climate is warm temperate maritime, with warm, moist summers and cool, wet winters. Mean annual rainfall for coastal areas ranges between 1200 mm in the south (Gisborne City) to 1600 mm in the north (Ruatoria township) (Fig. 1), and for inland areas between ~2500 mm in the south and ~4000 mm in the north, nearest to the crest of the Raukūmara Range (Hessell 1980). This region has a history of extreme erosion-generating storms (Kelliher et al. 1995) with 24 h rainfall intensities of ~150 mm and recurrence intervals near the coast of 3.6 years, and 2.6 years nearer to the main divide (Hicks 1995). A major cyclone (Cyclone Bola) in 1988 delivered on average between 300 and 600 mm of rain over a 5-day period, with the highest rainfall total of 900 mm recorded in Ūawa catchment (Fig. 1). The return interval for this event was estimated at 70 years (pers. comm., Dave Peacock, Gisborne District Council). This volatile climate contributes to high erosion rates (Water and Soil Directorate 1987).

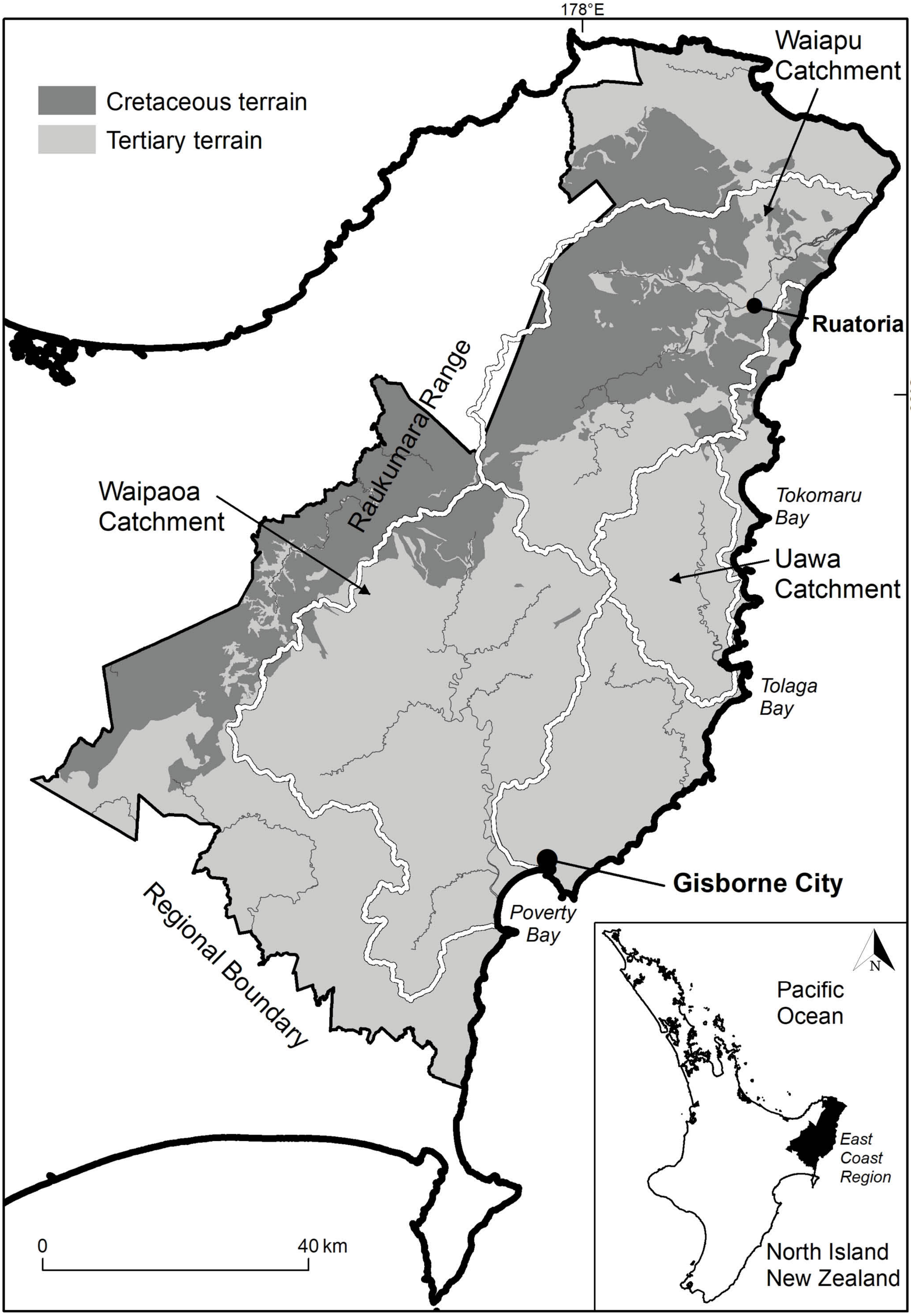

FIGURE 1: Location of major catchments and geological terrains within the East Coast region, North Island, New Zealand.

Data capture

A long-term perspective of the distribution, development, and remediation of actively eroding gullies has primarily been through photogrammetric interpretation of sequential aerial photography. Actively eroding gullies were identified as areas of exposed bedrock (i.e., devoid of vegetation) contiguous with the predominantly ephemeral channels that drained them (after Betts & De Rose 1999) but excluded adjacent areas of broken ground attributable to mass movement that retained a pastoral grass, shrubland or forest cover.

Marden et al. (2012) presented a regionwide analysis of changes in the distribution of gullies digitised from aerial photography flown before reforestation (~1957), and again after ~40 years of reforestation (1997). The region was re-flown in 2017, and this photography was used to relocate gullies that had remained actively eroding since 1997 (Fig. 2).

To account for gullies mapped as actively eroding in 1997 but no longer visible on the 2017 photography, their watershed area was re-digitised, and these gullies were recorded as having fully stabilised during the 1997–2017 measurement period. For cross-referencing purposes, if gullies digitised in 2017 existed in the landscape before this date, they were assigned the same unique number as in the earlier 1957 & 1997 data bases. New gullies initiated after 1997 were similarly assigned a unique number. All three data sets were digitised using MAPINFO, and we refer to the individual GIS-based mapped coverages by the date of photography (Fig. 2).

Data analysis

We documented changes in the spatial and temporal distribution of gullies over the past~20-year (1997–2017) period, which included further widespread land-use change, primarily from a pastoral grazing (sheep and beef) regime to exotic forest. We used the planting date for gullies established in exotic pines (predominantly *P. radiata*), and the year pastoral land was retired for 'managed' reversion (i.e., includes supplementary planting of indigenous seedlings) and/or natural 'passive' reversion, to establish temporal relationships of the effectiveness of these treatment options in stabilising gullies of varying size (Marden et al. 2005, 2008, 2011). Similar relationships were not attempted for gullies located within areas of well-established shrubland or indigenous forest, as the age of these vegetation types was unknown. Shrublands comprise early successional indigenous reverting species dominated by the myrtaceous species mānuka (*Leptospermum scoparium* J.R.Forest & G.Forst) and kānuka (*Kunzea ericoides var. ericoides* (A. rich) Joy Thomps.) (Connor & Edgar 1987), along with tree ferns and young broadleaved species (Clarkson et al. 1986) commonly found around forest margins, and on sites cleared for agriculture but subsequently found to be uneconomic (Newsome 1987). They represent several abandonment and reversion cycles, with each community having differing imbalances in their age, structure, and species composition (Smale 1994). At present, extant areas of primary *Nothofagus* forest are restricted to elevations above 600 m, extending to the tree line at 1050 m, and alpine–subalpine shrubland and grasslands on the highest parts of the Raukūmara axial range (Figs. 1 & 2) (McGlone 1988; Wilmshurst 1997), a Conservation Park with high cultural significance and the only 'wilderness' area in the North Island.

Attributes assigned to each gully included size (ha) and type (linear or amphitheatre), land cover (indigenous forest, shrubland reversion, exotic forest, pasture), catchment name, geological terrain (Cretaceous versus Tertiary), and the mapped occurrence of gullies located on Gisborne District Council's Land Overlay 3A. For each individual gully digitised in 2017, a measured planimetric area indicated that it had either remained active since 1997 or had been initiated after this date. Gullies that had failed after 1997 are referred to as '*new*' gullies. Gullies that had enlarged between measurement periods indicated that either they had not been treated, or, if treated, the treatment option was either inappropriate for the site, was insufficient for the feature, had yet to become effective, or had failed. Gullies present in 1997 but not in 2017 were deemed to have fully stabilised or '*closed*' between these measurement periods. Gullies that had reduced in size between measurement periods indicated that treatment had resulted in partial stabilisation only while other parts of the same gully remained *'active'*. Gullies initiated after each set of photography was flown but had stabilised before the next available photographic coverage have not been accounted for. Where a mix of different vegetation types was present, the land-cover attribute assigned to each gully was based on the dominant plant species present in the vicinity of the gully itself. Gullies initiated on pastoral land and subsequently stabilised in the absence of woody vegetation were recorded separately.

The regional distribution of actively eroding gullies (by number and composite gully area), and changes in their distribution between measurement periods were determined in ESRI (Environmental Systems Research Institute) Arc Map version 9.3. Analyses of gully density and proportional area affected by gullies within catchments, geologic terrains, vegetation types, and LO3A have been calculated based on the extent of hill country terrain only.

The 2017 aerial orthophoto database is in standard LINZ NZ Topo50 1:5000 tiles (2400m × 3600 m) and supplied in NZGD2000/NZTM datum. The mapping procedure and orthorectification software for comparing gullies mapped from photography flown at different times and scales is presented in Marden et al. (2012) as are details of the flight year, survey number, and nominal scale of aerial photography used.

Results

Spatial and temporal trends in gully distribution and affected area, 1997–2017.

Regionwide, during the 1997-2017 period, and across all land uses combined, 601 gullies fully re-stabilised and

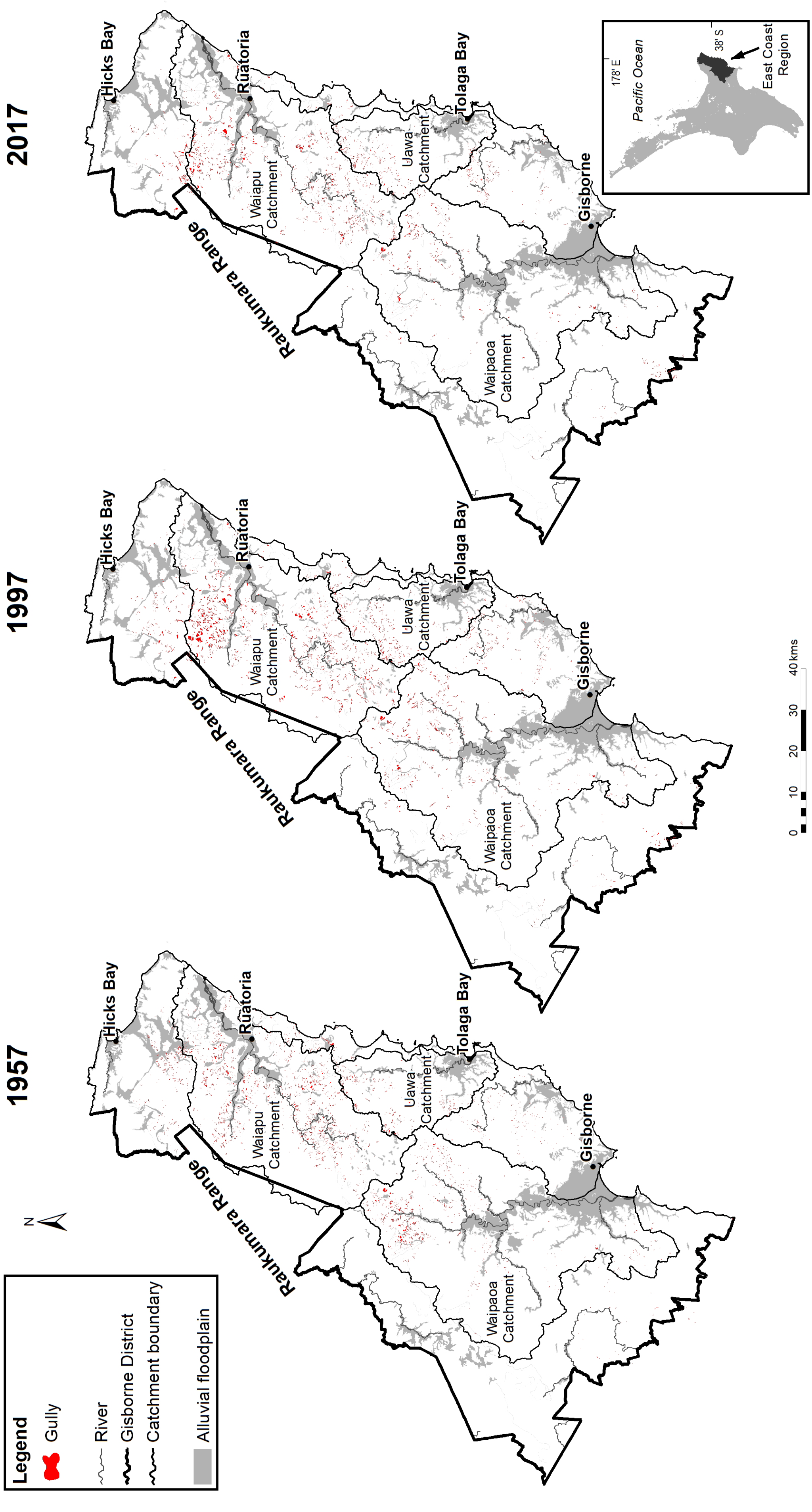

FIGURE 2: Regional distribution of actively eroding gullies (red) before remediation (1957) and for subsequent measurement periods 1997 and 2017, by catchment within the East Coast region, North Island, New Zealand.

315 new gullies were initiated (Table 1) resulting in a reduction in gully density from 0.28 to 0.25/km^2 and in composite gully area from 1.02 to 0.71 ha/km^2 (Table 2).

By 2017, 1864 individual gullies with a composite area of 5347 ha remained actively eroding. This represents a modest 13% reduction in gully numbers and a moderate net 31% decrease in gully composite area during this 20-year period (Tables 1 & 2).

Indigenous vegetation

During this period the incidence and composite area of gullies mapped within areas of indigenous forest increased by 37% and 26%, respectively, resulting in an increase in gully density from 0.04 to 0.06/km^2 and in composite gully area from 0.34 to 0.46 ha/km^2 (Table 2). By 2017, the most significant increase in gully activity occurred within the Cretaceous terrain (26%), primarily within the Raukūmara Conservation Park (Fig. 1), and to a lesser extent (12%) in similarly forested areas scattered throughout the Tertiary terrain (Table 3). By the end of the 1997-2017 measurement period, 119 (6%) of the regionwide total of 1864 gullies that remained active and 17% (887 ha) of the 5347ha composite gully area occurred within areas of indigenous forest (Table 2).

Within shrubland areas already present in 1997, and with the retirement of an additional ~4000 ha of partially reverted pastoral land to promote gully remediation through natural shrubland reversion, the incidence of gullies had by 1997 decreased by 23% and their composite area by 51%. Accordingly, gully density within shrubland areas decreased from 0.44 to 0.32/km^2 corresponding with a decrease in composite gully area from 1.90 to 0.89 ha/km^2 (Table 2). Reductions in both the total number and composite area of gullies were greater in shrubland areas located in the Cretaceous terrain (65%) than in the Tertiary terrain (31%) (Table 3). At the end of the 1997-2017 measurement period, 14% (263) of the regionwide total number of gullies (1864) and 14% (732 ha) of the total composite area affected by gullies (5347 ha) occurred within areas of shrubland reversion (Table 2).

Pastoral land

The planting of *Populus* (poplar) and *Salix* (willow) species proved successful in fully-stabilising 30 gullies each averaging 1.3 ha in size and in the partial-stabilisation of 21 gullies each averaging 2.7 ha in size. The co-existence of reverting shrubland within many of these gullies undoubtedly contributed to their stabilisation, more so than had gullies been planted in poles only. Conversely, for gullies averaging 4.5 ha or larger, and irrespective of the presence or absence of reverting shrubland, there was little to no sign that pole plantings had resulted in a reduction in gully activity or their size. During the 1997-2017 period, pole planting across 2363 hectares of pastoral land effectively reduced the composite area of actively eroding gullies by just 63 ha. Interestingly, while in the presence of grazing stock, and without any mitigation intervention, 48 gullies averaging 1.4 ha fully-stabilised and 101 gullies showed a reduction in size.

Gully occurrence and the affected area decreased by 45% and 59%, respectively, resulting in a decrease in gully density from 0.28 to 0.23/km^2, and in area from 0.79 to 0.49 ha/km^2 (Table 2). By 2017, 40% (741) of the regionwide total of actively eroding gullies and 29% (1574 ha) of the regionwide gully area remained associated with hill country areas retained in pastoral production (Table 2). Of this, the largest proportion (40%, 1216 ha) was located within the Tertiary terrain (Table 3).

Exotic forest

After the conversion of an additional ~20 000 ha of gully-prone pastoral land to forestry the incidence of gullies associated with this land use increased by 48% and their composite area by 20% concomitant with increases in gully density from 0.30 to 0.48/km^2 and in area affected from 1.27 to 1.39 ha/km^2 (Table 2). By 2017, regionwide, 40% (741) of all gullies and 40% (2154 ha) of the composite gully area of actively eroding gullies occurred within areas established in exotic forest (Table 2). At this time the largest concentration of afforested gullies that remained actively eroding (46%, 1414 ha) were located within the Tertiary terrain (Table 3).

Geological terrain

At the beginning of the 1997–2017 measurement period, the highest incidence of actively eroding gullies (1330, 62%) and the greatest proportion of the total composite area of land affected by gullies regionwide (4230 ha, 55%) occurred within the Tertiary terrain (Table 4). Since 1997, gully numbers within this terrain have decreased by just 5% from a density of 0.26 to 0.25/km^2 and gully composite area decreased by 28% thereby reducing the extent of this terrain affected by gully erosion from 0.82 to 0.60 ha/km^2 (Table 4). By 2017, despite significant investment in the remediation of gullies within the Tertiary terrain, the highest proportion (68%, 1262 gullies) of the regionwide total of gullies, and the highest concentrated area of eroding gullies (57%, 3064 ha), remained within this terrain (Table 4). Conversely, although the density of gullies within the Cretaceous terrain was initially higher at 0.34/km^2, the reduction in gully numbers by 2017 has been greater (27%) than in the Tertiary terrain and accordingly gully density decreased to 0.25/km^2. Correspondingly, the composite gully area within the Cretaceous terrain decreased by 34% resulting in a reduction in the extent of this terrain affected by gully erosion from 1.44 to 0.94 ha/km^2 (Table 4).

Catchment

Waiapu catchment at the beginning of the 1997-2017 measurement period had the highest incidence of the regionwide total of actively eroding gullies (976, 45%) and the greatest proportion of land area affected (3920 ha, 51%) (Table 5). By 1997, although there had been a significant 32% reduction in the extent of hill country affected by gullies from 2.45 to 1.68 ha/km^2, the highest proportion of the regionwide area of actively eroding gullies (50%, 2653 ha) that require further remediation

TABLE 1: Percentage change in regionwide distribution in gully numbers and composite gully area of *new* gullies initiated, those that *closed* /*partially closed* and those that remained *active* between measurement periods.

	1957-1997						1997-2017					
Gullies	**Active in 1957**	**Closed by 1997**	**Existing gullies enlarged by 1997**	**New**	**Total remaining active in 1997**	**Percent reduction/ increase 1957-1997**	**Closed by 2017**	**Partially closed by 2017**	**New**	**Total remaining active in 2017**	**Percent reduction 1997-2017**	**Percent reduction since 1957**
No.	3360	2341.	-	1131	2150	-36	601	-	315	1864	-13	-45
Area (ha)	5600	2367	1645	2832	7710	+27	1086	2100	823	5347	-31	-5

TABLE 2: Changes in the gully density (no./km^2) and composite area (ha/km^2) based on the areal extent of hill country occupied by each land use type before remediation (1957), in 1997 and in 2017. Figures in parentheses are percentages of the regionwide total number of gullies and composite area present at the time of measurement. Note: the planting of extensive areas of exotic forest to mitigate gully erosion didn't commence until the early 1960s.

Land use	**Active in 1957**				**Active in 1997**				**Percent increase/ decrease 1957-1997**		**Active in 2017**				**Percent increase/ decrease 1997-2017**		**Percent increase/ decrease 1957-2017**	
	No. gullies	**No. gullies/ km^2**	**Gully area (ha)**	**Gully area/ km^2**	**No. gullies**	**No. gullies/ km^2**	**Gully area (ha)**	**Gully area/ km^2**	**No. gullies**	**Gully area**	**No. gullies**	**No. gullies /km^2**	**Gully area (ha)**	**Gully area / km^2**	**No. gullies**	**Gully area**	**No. gullies**	**Gully area**
Pasture	3160 (94)	0.65	5319 (95)	1.06	1350 (63)	0.28	3850 (50)	0.79	-57	-28	741 (40)	0.23	1574 (29)	0.49	-45	-59	-77	-70
Exotic forest	-	-	-	-	385 (18)	0.30	1720 (22)	1.27	-	-	741 (40)	0.48	2154 (40)	1.39	+48	+20	-	-
Indigenous forest	25 (1)	0.01	28 (0.5)	0.01	75 (3)	0.04	660 (9)	0.34	+67	+96	119 (6)	0.06	887 (17)	0.46	+37	+26	+79	+97
Shrubland	175 (5)	0.22	253 (4.5)	0.33	340 (16)	0.44	1480 (19)	1.90	+49	+83	263 (14)	0.32	732 (14)	0.89	-23	-51	+33	+65
Totals	3360 (100)	0.44	5600 (100)	0.74	2150 (100)	0.28	7710 (100)	1.02	-36	+27	1864 (100)	0.25	5347 (100)	0.71	-13	-31	-45	-5

TABLE 3: Percentage change in regionwide distribution in gully area (ha) by vegetation type on 5135 km² of Tertiary and 2417 km² of Cretaceous hill country terrain before remediation (1957), in 1997, and 2017. Figures in parentheses are percentages of the total composite gully area present within each terrain at the time of measurement. Note: the planting of extensive areas of exotic forest to mitigate gully erosion didn't commence until the early 1960s.

Land use	1957-1997						1997-2017		Percent increase/ decrease 1997-2017		Percent increase/decrease 1957-2017	
	Area active in 1957 (ha)		Area active in 1997 (ha)		Percent increase/decrease 1957-1997		Area active in 2017(ha)					
Terrain	Tertiary	Cretaceous	Tertiary	Cretaceous	Tertiary	Cretaceous	Tertiary	Cretaceous	Tertiary	Cretaceous	Tertiary	Cretaceous
Pasture	2479 (97.6)	2840 (93)	2440 (58)	1410 (41)	-2	-50	1216 (40)	366 (16)	-50	-74	-51	-87
Indigenous forest	3 (0.1)	25 (1)	21 (0.5)	639 (18)	+86	+96	24 (<1)	862 (38)	+12	+26	+87	+97
Shrubland	58 (2.3)	195 (6)	590 (14)	890 (26)	+90	+78	410 (12)	314 (14)	-31	-65	+86	+38
Exotic forest	-	-	1179 (27.5)	541 (15)	-	-	1414 (46)	741 (32)	+17	+27	-	-
Totals	2540 (100)	3060 (100)	4230 (100)	3480 (100)	+40	+12	3064 (100)	2283 (100)	-28	-34	+17	-25

TABLE 4: Percentage change in regionwide distribution in gullies (no./km²) and composite gully area (ha/km²) on 5135 km² of Tertiary and 2417 km² of Cretaceous hill country terrain before remediation (1957), in 1997, and 2017. Figures in parentheses are percentages of regionwide totals present at the time of measurement.

Terrain	Active in 1957				Active in 1997				Percent increase/ decrease 1957-1997		Active in 2017				Percent increase/ decrease 1997-2017		Percent increase/ decrease 1957-2017	
	No. gullies	No. gullies/ km²	Gully area (ha)	Gully area/ km²	No. of gullies	No. gullies/ km²	Gully area (ha)	Gully area/ km²	No. gullies	Gully area	No. of gullies	No. gullies /km²	Gully area (ha)	Gully area / km²	No. gullies	Gully area	No. gullies	Gully area
Tertiary	1900 (57)	0.37	2540 (45)	0.49	1330 (62)	0.26	4230 (55)	0.82	-30	+40	1262 (68)	0.25	3064 (57)	0.60	-5	-28	-34	-59
Cretaceous	1460 (43)	0.60	3060 (55)	1.27	820 (38)	0.34	3480 (45)	1.44	-46	+12	602 (31)	0.25	2283 (43)	0.94	-27	-34	+17	-25
Total regionwide	3360 (100)	0.44	5600 (100)	0.74	2150 (100)	0.28	7710 (100)	1.02	-36	+27	1864 (100)	0.25	5347 (100)	0.71	-13	-31	-45	-5

remains within this catchment (Table 5). In contrast, the area affected by gullies within the earliest of the planted exotic forests in Waipaoa catchment decreased by 40% and resulted in a reduction in the extent of this catchment affected by gully erosion from 0.76 to 0.46 ha/km^2. By the end of the 1997-2017 measurement period, just 17% of the regionwide area of gullies that require further remediation occurred within Waipaoa catchment. Within Ūawa catchment, and due largely to the initiation of new gullies during Cyclone Bola, the density of active gullies had by 1997 increased from 0.58 to 0.67/km^2. The subsequent establishment of extensive areas of exotic forest had by 2017 stabilised many of the smaller gullies thereby reducing the area affected from 1.67 to 1.53 ha/km^2 (Table 5). A similar response to the planting of exotic forest occurred in the many smaller catchments, and within a similar time frame (Table 5).

Status of active gullies recorded on Land Overlay 3A in 2017

Overall, 77% (1299) of the regionwide total of 1864 gullies considered to be actively eroding in 2017 and 75% (4034.2 ha) of the 5347 hectares affected by gully erosion regionwide, occurred within hill country designated as LO3A (Table 6). By terrain, gully density (3.89/km^2) and the area affected (10.17 ha/km^2) was highest within the Cretaceous terrain. By catchment, although gully density was highest within the smaller Uawa catchment (3.41/km^2), the area affected by gullies was greater within Waiapu catchment (9.36 ha/km^2) (Table 7). By land use, although gully density and the area affected by them remains significant across areas in pastoral production, the highest density (1.16/km^2) and area affected (3.54 ha/km^2) occurs within areas of exotic forest, more so in parts of LO3A only recently converted to exotic forest (e.g., Uawa catchment) (Table 7) where plantings have yet to become effective in stabilising gullies. Although the incidence of gullies within remaining areas of indigenous forest is low (0.18/km^2) they are individually large and collectively affect 1.43 ha/km^2 (Table 7). Though more numerous within areas of shrubland reversion, gullies collectively affect just 1.08 ha/km^2 (Table 7). Furthermore, across each of the land uses, the incidence and area affected by gullies within LO3A is higher than for the regionwide area of hill country associated with each land use type (Table 7). Unsurprisingly, the density of gullies (2.60/km^2) and affected area (8.07 ha/km^2) within LO3A is an order of magnitude greater than is associated with the total area of hill country present regionwide (Table 6).

Gully size

Regionwide, following the initiation of 315 new and generally smaller-sized gullies, the proportion of gullies <2 ha in size has increased to 65%, those within the 2–10 ha size range due either to part- or full-stabilisation since 1997 decreased to 29%, while the number of gullies >10 ha (6%) has remained unchanged (Fig. 3).

Discussion

Trends in gully initiation, development, and remediation

Not all gullies formed at the same time or developed at the same rate (Marden et al., 2005). They developed earliest and fastest in areas of Cretaceous terrain (Gage & Black 1979; De Rose et al. 1998; Marden et al. 2005, 2008, 2011, 2014; Parkner et al. 2006, 2007) where structurally weak and fault-crushed bedrock coincide with high rainfall regimes (Fuller & Marden 2008). These factors predispose such areas to gully erosion and associated mass movement processes, the mechanism by which many gullies increase in size and develop as amphitheatre-shaped, fluvio-mass movement gully complexes (De Rose et al. 1998; Fuller & Marden 2010, 2011; Fuller et al. 2020).

Before remediation strategies were introduced 60 years ago there were 3360 clearly identifiable eroding gullies with a combined area of 5600 ha (Table 1), affecting ~0.7% of the region's total hill country area. At this time, 94% of gullies and 95% of their composite area were located on pastoral hill country, and the balance within areas of indigenous forest and/or reverting shrubland (Table 2).

The re-afforestation of extensive area of gully-prone pastoral hill country specifically for erosion control purposes began with the planting of an initial ~35 000 ha (1961–1985) of fast-growing exotic tree species. Areas targeted for afforestation were primarily located within the Cretaceous terrain, specifically the headwater reaches of the Waipaoa and Waiapu catchments where the concentration of gullies was greatest (De Rose et al. 1998; Marden et al. 2005, 2014). Here, gullies in the 1–2 ha size range stabilised quickest. Where plantings had been established for the best part of a rotation of *P. radiata* (c. 27 years), many gullies up to 10 ha in size fully stabilised and remained unaffected by future storms including Cyclone Bola in 1988 (e.g., Fig. 4).

While these early plantings proved successful in stabilising 2341 gullies, this was countered by the initiation of 1131 new gullies (Table 1) during Cyclone Bola. Gully development was severest in areas of erosion-prone pastoral hill county due in part to high rates of rainfall runoff leading to incision within incipient drainage channels, and in part to the expansion of a significant number of already sizeable gullies that had remained untreated before this event. The increase in severity in gully erosion associated with pastoral land was greatest within the Tertiary terrain and within Waiapu catchment.

While past storms have probably contributed to the overall susceptibility of indigenous forest to the initiation of new gullies (Parkner et al. 2006, 2007; Betts et al. 2003; Kasai et al. 2005), Cyclone Bola provided the trigger required to initiate the significant increase in the extent of gullying within remnant areas of indigenous forest in both terrains (Tables 2 & 3). Other influential

TABLE 5: Percentage change in the distribution in gully number (no./km^2) and composite area (ha/km^2) of actively eroding gullies on hill country, by catchment, before remediation (1957), in 1997 and in 2017. Figures in parentheses are percentages of regionwide totals present at the time of measurement.

Terrain	Active in 1957				Active in 1997				Percent increase/ decrease 1957-1997		Active in 2017				Percent increase/ decrease 1997-2017		Percent increase/ decrease 1957-2017	
	No. gullies	No. gullies/ km^2	Gully area (ha)	Gully area / km^2	No. gullies	No. gullies /km^2	Gully area (ha)	Gully area / km^2	No. gullies	Gully area	No. gullies	No. gullies/ km^2	Gully area (ha)	Gully area / km^2	No. gullies	Gully area	No. gullies	Gully area
Waipaoa (1987 km^2)	872 (26)	0.44	1438 (26)	0.72	447 (21)	0.23	1519 (20)	0.76	-49	+5	385 (21)	0.19	917 (17)	0.46	-14	-40	-56	-36
Waiapu (1582 km^2)	1158 (35)	0.73	2644 (47)	1.67	976 (45)	0.62	3920 (51)	2.45	-16	+33	786 (42)	0.50	2653 (50)	1.68	-19	-32	-32	+56
Ūawa (504 km^2)	414 (12)	0.82	514 (9)	1.02	290 (13)	0.58	844 (11)	1.67	-30	+39	337 (18)	0.67	769 (14)	1.53	+14	-9	-19	+33
Other (3479 km^2)	916 (27)	0.26	1004 (18)	0.29	437 (21)	0.13	1427 (18)	0.41	-52	+30	356 (19)	0.10	1008 (19)	0.29	-19	-29	-61	+0.4
Total regionwide (7552 km^2)	3360 (100)	0.44	5600 (100)	0.74	2150 (100)	0.28	7710 (100)	1.02	-36	+27	1864 (100)	0.25	5347 (100)	0.71	-13	-31	-45	-5

TABLE 6: Density (no./km^2) and composite area (ha/km^2) of gullies actively eroding in 2017 across Tertiary and Cretaceous terrain classified as LO3A. Figures in parentheses are percentages of gullies, and area of hill country affected, within LO3A, and across hill country regionwide.

Terrain classified as LO3A	No. gullies	No. gullies/km^2	Gully area (ha)	Gully area (ha/km^2)
Tertiary (285 km^2)	462 (25)	1.62	1848 (34)	6.61
Cretaceous (215 km^2)	837 (45)	3.89	2186 (41)	10.17
Total area of LO3A (500 km^2)	1299 (70)	2.60	4034.2 (75)	8.07
Regionwide hill country (7752 km^2)	1864	0.24	5347	0.69

TABLE 7: Density (no./km^2) and composite area (ha/km^2) of gullies actively eroding in 2017 within LO3A, by catchment, and vegetation cover. Figures in parentheses are percentages by land use, and by catchment.

Catchment and area of LO3A	Pasture				Exotic forest				Indigenous forest				Shrubland				Totals by catchment			
	No. gullies	No. gullies /km^2	Gully area (ha)	Gully area /km^2	No. gullies	No. gullies /km^2	Gully area (ha)	Gully area /km^2	No. gullies	No. gullies /km^2	Gully area (ha)	Gully area /km^2	No. gullies	No. gullies /km^2	Gully area (ha)	Gully area /km^2	No. gullies	No. gullies /km^2	Gully area (ha)	Gully area /km^2
Waiapu (232 km^2)	222 (52)	0.96	559 (55)	2.41	276 (48)	1.19	886 (50)	3.82	47 (53)	0.20	464 (65)	2.00	87 (43)	0.38	263 (49)	1.14	632 (49)	2.72	2171.7 (54)	9.36
Waipaoa (108 km^2)	86 (20)	0.80	149 (15)	1.38	148 (25)	1.37	459 (26)	4.25	1 (1.0)	0.01	3 (<1)	0.03	31 (15)	0.29	103 (19)	0.95	264 (20)	2.44	714.0 (18)	6.61
Ūawa (68 km^2)	43 (10)	0.63	91 (9)	1.34	120 (21)	1.76	317 (18)	4.66	5 (6)	0.07	8 (1)	0.12	64 (32)	0.94	129 (24)	1.90	232 (18)	3.41	544.2 (13)	8.00
Other (92 km^2)	76 (18)	0.83	207 (21)	2.25	37 (6)	0.40	110 (6)	1.20	36 (40)	0.40	242 (34)	2.63	20 (10)	0.20	46 (8)	0.50	171 (13)	1.86	604.3 (15)	6.57
LO3A totals (500 km^2)	426 (100)	0.85	1006 (100)	2.01	580 (100)	1.16	1772 (100)	3.54	89 (100)	0.18	717 (100)	1.43	202 (100)	0.40	541 (100)	1.08	1299 (100)	2.60	4034.2 (100)	8.07

factors likely included intrinsic gully dynamics (Fuller & Marden 2011), variations in lithology, structural controls, climate, and the steepness of the topography. Also significant, has been the degradation of the original vegetation through the sustained browsing of the canopy and understorey by 'recently' introduced (during European settlement) mammals (Wallis 1966; James 1969), and the consequent deterioration of the forest canopy by wind damage in the early 1980s (Littlejohn 1984). These same factors will probably be the most significant natural drivers of further gully erosion within remaining areas of indigenous forest well into the future.

The incidence of gullies within areas of reverting shrubland increased following Cyclone Bola (Tables 2 & 3) of which the majority were associated with large tracts of Tertiary hill country where reversion at that time was either not of a sufficient age, density, or stature to ameliorate gully development.

While the early plantings of exotic forest proved successful in reducing the area affected by gully erosion, Cyclone Bola triggered a significant increase in new gullies and expansion of existing gullies within the exotic forest estate. This included gullies that had been treated but where treatment proved to be insufficient and/or inappropriate for the size of the feature, and those considered to be beyond remediation (i.e., 'badass' gullies ≥10 ha) (Marden et al. 2014, 2018). The response following Cyclone Bola was to convert a further ~100 000 ha of the most severely damaged areas of pastoral land to exotic forest. By 1997, a significant 22% (1720 ha) of the regionwide composite area of actively eroding gullies occurred within the exotic forest estate (Table 2), and primarily within the Tertiary terrain (Table 3) and in Waiapu catchment (Table 5). Unaccounted for, however, are the number of gullies within the forest estate that likely stabilised during the short period between their initiation and remapping in 1997 and, therefore, the total number of new gullies initiated during this storm.

The highest proportion of the regionwide total of gullies (63%) and 50% of the composite gully area present at this time occurred in areas retained in pastoral production (Table 2), and predominantly within the Tertiary terrain (Table 3).

Across all land uses combined, the regionwide composite gully area had by 1997 increased to 7710 ha (Table 1), ~0.9% of the region's hill country area, 27% greater than existed before remediation efforts began.

During the subsequent, and shorter, 1997–2017 measurement period, 315 additional gullies comprising 823 ha were initiated regionwide (Table 1). While gully expansion within areas of indigenous forest increased, those within areas of shrubland reversion decreased (Table 2), more so within the Cretaceous terrain (Table 3) where an additional ~4000 ha of uneconomic pastoral hill country was retired for reversion to occur either through passive means or managed through the plantings of indigenous shrubland species (e.g., mānuka). Regionwide, of the 601 gullies deemed to have stabilised ('closed') during this period (Table 1), 74% were located within the exotic forest estate. Ironically, despite the success of this treatment option, and as a further

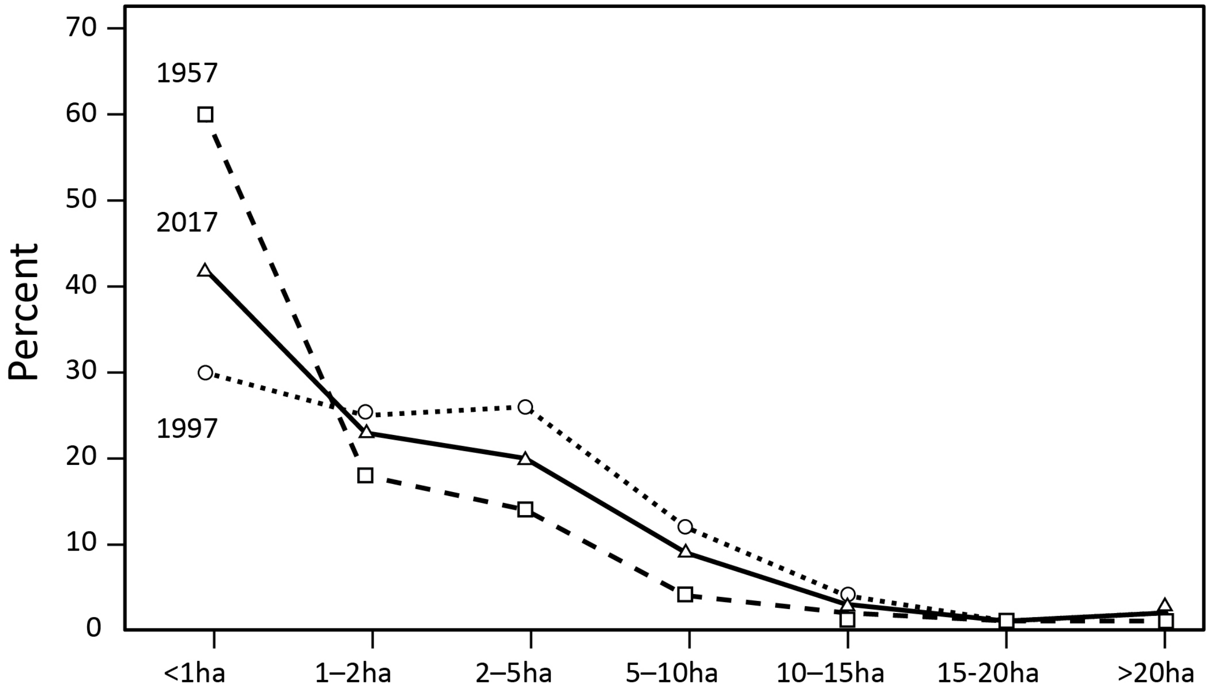

FIGURE 3: Regionwide change in the proportion of gully sizes before remediation (1957), in 1997, and in 2017.

20 000 ha of gully-prone pastoral land transitioned to exotic forest, the number of gullies located with exotic forests increased by 48% and the area affected increased by 20% (Table 2). By the end of the 1997–2017 period, the highest proportion (40%) of the regionwide total number of gullies at a density of 0.48/km^2, and 40% of their composite area occupying 1.39 ha/km^2 occurred within areas replanted in exotic forest (Table 2).

By terrain, the highest proportion of gullies that remain active are located within the Tertiary terrain (Table 3) where a significant proportion of exotic forest plantings are of young age and have yet to effectively stabilise the larger-sized gullies. Irrespective of when (1957–1997 vs 1997–2017) exotic forest plantings are established, the probability of gullies of equivalent size stabilising in response to planting is similar in both the Cretaceous and Tertiary terrains. For gullies ≤1 ha there is an 80 to >90% probability that they will stabilise within a decade of planting, a 60% probability for gullies ≥1 and ≤5 ha in size, and for gullies ≥5 and <10 ha, an even chance of stabilising within a rotation (~24–27 years) of *P. radiata* (Marden et al. 2011).

Of the regionwide total area affected by gullies in 2017 (5347 ha), 29% occurred on hill county retained in pastoral production, a reduction of 59% since 1997. In contrast, the composite area affected by gullies within

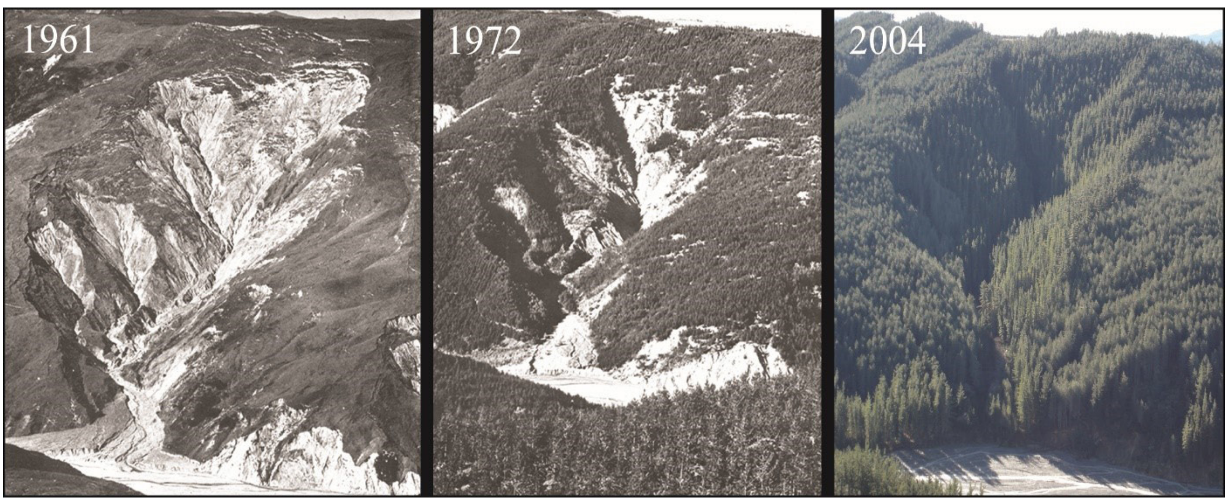

FIGURE 4. Pre- (1961) and post-reforestation (1972, 2004) photographs of a medium-sized gully in Te Weraroa Stream, Mangatū Forest, within the Cretaceous terrain. (The 1961 and 1972 photographs are courtesy of J. Johns; the 2004 photograph was taken by M. Marden.) (Source: Marden et al. 2005).

areas of indigenous forest increased by 26% whereas in areas of indigenous shrubland, natural reversion resulted in a 51% decrease in gully area (Table 2).

Regionwide, during the 1997-2017 period, the composite area of those gullies that had fully-stabilised (1086 ha) together with those that had part-reduced in size (2100 ha) exceeded the area of new gullies initiated (823 ha) (Table 1). This resulted in a significant 31% reduction in gully area to 5347 ha ~0.6% of the region's hill country area.

Since remediation efforts began, and irrespective of differences in the duration of the 1957–1997 and 1997–2017 measurement periods, approximately twice as many gullies regionwide have been successfully stabilised (2341 and 601, respectively) as new gullies initiated (1131 and 315, respectively), resulting in an overall net 45% reduction in the number of eroding gullies. The most significant gains in reducing the density and area affected by gullies has been through the retirement and afforestation (exotic and indigenous) of extensive areas of the most severely eroded areas of pastoral hill country. These successes have however been countered by significant increases in the initiation of new gullies both within areas that remain in pastoral production and in remnant areas of indigenous forest. Thus, regionwide, the area occupied by gullies as at 2017 (5347 ha) was only 5% less than the 5600 ha of eroding gully present before remediation treatments began 60-years ago (Table 1). Furthermore, as of 2017, with 4034 ha of actively eroding gullies (75% of the total regionwide composite gully area remaining on land identified as Land Overlay 3A) (Table 6) required to have an effective tree cover by 2021, it is apparent that the combined goals of the East Coast Forestry Project and the Gisborne District Council's Combined Regional and District Plan have yet to be met. Similarly, there are ~2172 ha of actively eroding gully (54% of the total regionwide composite gully area) in need of treatment within Waiapu catchment (Table 7). Here again, the goals set as part of the Crown's 'Relationship Accord' with Ngāti Porou, and the Gisborne District Council (Restoring the Waiapu Catchment), of accelerating and completing LO3A works plans (including the treatment of gullies) and maintaining an effective tree cover, post-2021, remain unfulfilled.

With climate change predictions for this region suggesting drier overall but with larger than national average increases in rainfall intensity during (ex)tropical storms[2], our findings support modelled predictions that unless a targeted gully-remediation programme is fully-implemented, catchment sediment loads will probably double within the timeframe of a rotation of *P. radiata*. Conversely, the completion of such a programme could effectively halve catchment sediment loads within a similar timeframe, and remain constant thereafter, but only if new gullies are identified and treated as they develop (Herzig et al. 2011).

The vision for the restoration of the Waiapu catchment is "Ko te mana ko te hauroa o te whenua; ko te hauroa o nga awa; ko te hauroa o te iwi – Healthy land, healthy rivers, healthy people". Further delays or non-completion of gully remediation targets will however jeopardise the desired outcomes of environmental restoration, economic profitability, cultural revitalisation, and social prosperity (Ministry for Primary Industries 2014).

That said, due to the continued supply of large volumes of sediment generated from gullies alone, combined with the legacy of stored bedload sediment, the current high rates of suspended sediment yield of the major river channels delivered to both the near- and off-shore marine ecosystems is unlikely to change in the short to medium term.

Hydrological influences and root-reinforcement contributions to gully remediation

Assessments of the effectiveness of past reforestation efforts in New Zealand have largely been unanimous in finding that the re-establishment of a permanent evergreen forest cover (exotic or indigenous) is an effective means of stabilising both fluvial and fluvio-mass movement gullies, and the processes associated with their initiation and development. The key determinants that influence the success/failure rate of exotic reforestation in the remediation of gully erosion are the size, shape (linear versus amphitheatre), and activity of each gully at the time of planting. Of the remediation options currently used to stabilise gullies, the planting of exotic species, particularly *P. radiata*, has proven most successful. The stabilisation of gullies is largely attributed to the combined hydrological and mechanical influences associated with the re-establishment and maintenance of a cover of woody vegetation. Indeed, the success of the early exotic forest plantings in restoring slope stability has been attributed to high root mass production and an efficient utilisation of available soil-water (Pearce et al. 1987), thereby producing the stronger and drier soils required for maintaining long-term slope stability (Zhang et al. 1991, 1993).

Past gully remediation efforts were also found to be most successful where the planting of both the watershed surrounding each gully and the gully itself were staged. For example, the strategy for the 7.6 ha gully depicted in figure 4 involved the planting of *Pinus nigra* (in 1962) on the less-mobile higher slopes within the watershed surrounding this gully. Once these plantings were well established, and after the more open slopes immediately flanking this gully showed signs of improved stability, *P. radiata* was then planted (1966) to reduce the potential reoccurrence of mass failure (Dolman, 1982; Pearce et al. 1987; Phillips et al. 1991; Marden et al. 1992). Key indicators that stability within this gully had been restored included channel incision and narrowing, and the recolonisation of the debris fan by indigenous shrubby species, supplemented by further plantings of exotics. These changes in the dynamism of gully/channel behaviour signal a modulation of the connectivity between gullies and perennial streams, and probable reduction in the rate of sediment delivery to the larger drainage network (Kasai et al. 2001, 2005). A similar response has been widely documented, notably in Europe following major reforestation a century ago (Garcia-Ruiz et al. 1997; Piégay & Salvador 1997; Liébault & Piégay 2001; Surian & Rinaldi 2003).

However, erosion-control funding programmes introduced after Cyclone Bola, including the ECFP (in 1992), did not provide for the possibility that a significant number of the most actively eroding gullies targeted for afforestation would require, and indeed have benefited from a staged planting programme. Instead, as there was no provision to replant parts of gullies where the initial plantings had failed (blanking), many gullies enlarged and continued to generate sediment at a high rate for longer.

For shrubland reversion to passively recolonise and successfully stabilise existing gullies, the critical variables include gully size and activity, the processes (fluvial incision vs mass movement) that formed them, and whether the watershed surrounding each gully is included or excluded as part of the management strategy. Secondary influences will include the density, age, and shrubland species composition present within and surrounding each gully. Animal control will also prove crucial, as sustained browsing of the canopy and understorey[3, 4] increases the susceptibility of shrubland to slope failure (Wallis 1966; James 1969), a precursor to the development of many new gullies. As previously demonstrated by Marden and Rowan (1993) and by Bergin et al. (1995), stand age and density have a significant influence on the degree of protection provided by regenerating shrubland. For example, the rate of evapotranspiration and reductions in runoff rates within fully-stocked stands of shrublands comprising early successional species dominated by mānuka and kānuka are akin to that of a closed-canopy stand of *P. radiata* (Rowe et al. 1999). A significant drawback, however, is that kānuka would take twice as long (~16 years) and require an average stand density of ~13 000 stems/ha (Bergin et al. 1995) before their root systems would afford a comparable improvement in slope stability to that of *P. radiata* (Watson & O'Loughlin 1985; Ekanayake et al.1997; Watson et al. 1994, 1999; Watson & Marden 2004).

An alternative option to passive reversion is managed reversion through the supplementary planting of shrubland seedlings, of which mānuka is the most common of the early-colonising shrubland species planted for erosion control in this region (Marden et al. 2020). If established at densities of ~1100 stems/ha, evapotranspiration rates and root-reinforcement contributions to improving slope safety will naturally take longer than for fully-stocked stands of passively reverting shrubland. Variable planting density rates and plant mortality, resulting in under-stocking, would further delay the effectiveness of plantings on the more active and harsh slopes flanking gullies. Nonetheless, increasing the planting density, reducing early seedling mortality by better management of weed competition, and/or by replanting (blanking) would improve the erosion mitigation effectiveness of supplementary mānuka plantings.

As previously documented in Marden et al. (2012) a small proportion of very small gullies located on pastoral hill country stabilised without intervention. Similarly, during the 1997-2017 period, and in the absence of storms, their amelioration occurred through natural recolonisation by grass, bracken, and weeds alone. Although the use of traditional soil conservation species including *Populus* (poplar) and *Salix* (willow) has proven successful for stabilising on-farm gullies, their effectiveness diminishes with increasing gully size and activity. The greatest potential use of pole plantings should be targeted at future-proofing incipient drainage lines against the initiation and development of gullies.

Future management of gullies within exotic production forests

Originally established as 'protection forests' to remediate gully and associated mass movement in areas of Cretaceous terrain, a change in forest status to 'production-protection forests' saw their management change towards the production of harvestable timber. While concerns were expressed that the harvesting of these inland forests would result in the reactivation of gully and mass movement erosion, these concerns didn't eventuate, at least not for those gullies that had fully-stabilised prior to harvesting. This can be attributed to: (i) residual (post-harvest) soil-root reinforcement for a 12 to 15-month period following harvesting; (ii) the fast growth rate of the replacement crop of *P. radiata* to form a closed canopy and extensive root system within ~8 years of replanting; and (iii) the absence of significant storms.

Conversely, within the Tertiary terrain, most of the exotic forest estate is located on steeper and shorter slopes that flank deeply incised channels. Here, forest removal results in a more spontaneous increase in surface runoff, thereby heightening the risk of initiating the very processes that cause gullies to form in the first place. The risk of reactivating gullies also increases as the watershed surrounding gullies is progressively harvested, more so should the entire watershed be harvested within a short time frame, and particularly for those gullies where the area of the watershed is significantly larger than the gully itself. Additionally, the practice of harvesting trees from the watersheds of gullies before they fully-stabilise further increases the risk of their reactivation (Fig. 5).

At the time of establishment of exotic forests for erosion control it was normal practice to plant pines at between 1250-1500 stems ha^{-1} and from ridge-top to the edge of stream channels. This inhibited the seeding and growth of early-colonising indigenous shrubland species as groundcover particularly along stream margins. As a result, following forest removal and in the absence of riparian plantings to intercept sediment and woody debris and prevent its mobilisation to the wider stream network, the off-site impacts have in places been significant (Beetham & Grant 2006; Marden et al. submitted[a]).

[a] Marden, M., Seymour, A., Watson, A. Effect of changes in water balance and root reinforcement on landslide occurrence and sediment generation following the harvesting of *P. radiata* (D.Don) on Tertiary terrain, eastern North Island, New Zealand. *New Zealand Journal of Forestry Science.* (submitted 2022).

FIGURE 5. Actively eroding gully located within a *P. radiata* production forest. Forest removal before significant groundcover vegetation has established within the most active part of the gully will probably result in the remobilisation of sediment and woody debris by storms following future harvests. (Photography taken in 2004 courtesy of Malcolm Penn, Ministry for Primary Industries).

In this region the volume of pine residue remaining on-site after harvest is greater than in other regions of New Zealand (Gisborne District Council 2020). A contributing factor is the poor quality of timber established on unstable slopes surrounding gully systems thus the volume of pine residue remaining after harvest is higher than on the more fertile and stable parts of forests. Currently there are 741 actively eroding gullies located within the exotic forest estate and when harvested a significant volume of pine residue is likely to be remobilised during future storms and delivered to the wider stream network. The majority – but not all – forested gullies are located within land classified as either 'orange zone', with a high erosion risk, or 'red zone', where the erosion risk is very high (National Environmental Standard for Plantation Forestry [NES-PF], Ministry for Primary Industries 2018). Under the NES-PF, resource consents are required for areas of proposed afforestation and for the replanting of forests located within the red zone. Additionally, it is acknowledged that the replanting of plantation forests in the same locations as previously may not be appropriate, and that in places a different species (e.g., a mix of indigenous species) may be better suited to mitigating any potential increased risk of erosion and sedimentation. Also, both territorial and regional council regulations require that exotic plantings not occur within setback distances of 5 m of perennial rivers with a bank-full channel width of <3 m, and within 10 m of streams with a bank-full channel width of 3 m or more. While an integral component of the drainage network, there are currently no specific specifications regarding planting setback distances for gullies.

As previously shown gullies are the main source (Marden et al. 2005, 2008, Herzig et al. 2011) and conduit for the transportation and delivery of sediment to the wider drainage network. Forty percent of the 1864 gullies that remain actively eroding, and 40% of the composite area affected by gullies regionwide is located within exotic forests. For the larger and more actively eroding gullies, particularly those located within, but not exclusive to, red- and orange-zoned land, forest removal will almost certainly increase the risk of mass movement and fluvial incision within the gullies themselves. Furthermore, the risk of the remobilisation and delivery of increased volumes of sediment and woody debris to downstream environments will remain for an extended post-harvest period. Thus, and especially for these gullies, site-specific setback distances based on local physical site characteristics, as opposed to the set distances prescribed for perennial stream channels mandated in the NES-PF, would provide a more effective erosion mitigation outcome. An assessment of setback distances considered appropriate for individual gullies should be based on: (i) their size, shape (linear versus amphitheatre) and degree of activity; (ii) slope length and steepness; (iii) type of erosion process (mass movement or surface erosion) on slopes flanking each gully; (iv) the size of the gully relative to its watershed area; (vi) the location of the gully within its watershed (i.e., lower or headwater reaches of its watershed); (vii) the type, diversity and extent of existing vegetation at the time of planting; (viii) an assessment of the difficulties and cost of access at the time of harvest; and (ix) the potential for gully reactivation and mobilisation of sediment and woody debris following felling and retrieval of trees.

These criteria should also be applied to the larger of the numerous gullies located within orange- and red-zoned areas that remain in pastoral production and for which the most practical treatment option(s) will likely include exotic afforestation, reversion by indigenous shrubland species, or a combination of these treatments.

If tree species with a commercial value are to be planted and harvested within watersheds surrounding the larger and/or more active of the eroding gullies located within orange- and red-zoned land, plantings should be restricted to a position well-upslope of the active margin of each gully. Where possible, the planting boundary should be aligned with a natural break in slope, such as a change from a concave upper slope to a steeper, convex lower slope. This would, in effect, promote the development of a wide riparian buffer (e.g., light green in Figs. 6 & 7) between a harvestable crop and the actively eroding slopes flanking gullies. The establishment of faster-growing exotic species on the more accessible (from a planting and harvesting perspective) upper slopes within the watershed surrounding each gully (Figs. 6 & 7) then provides a microclimate better suited to the natural seeding of endemic shrubland species and their re-colonisation of open areas of bare ground. At the time of harvesting the commercial species, shrubland reversion of a marginal buffer could potentially entrap a significant volume

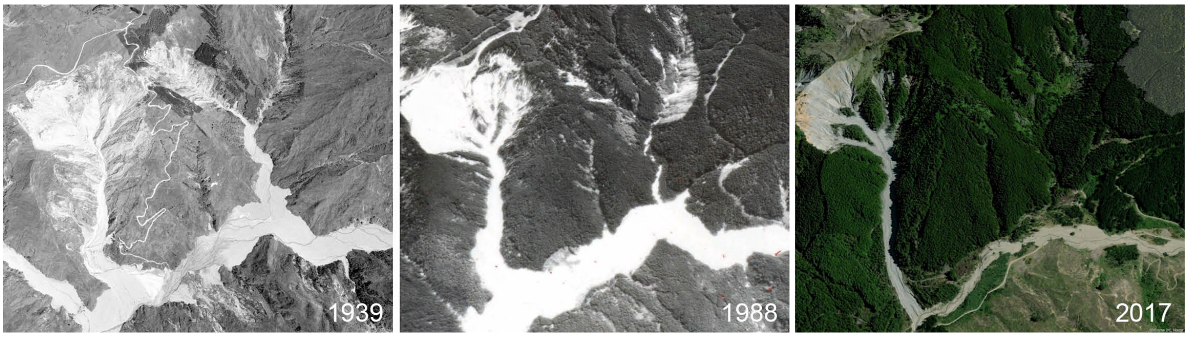

FIGURE 6: Part of Te Weraroa Stream catchment, Mangatū Forest within the Cretaceous terrain. Amphitheatre-shaped, gully, mass-movement complex (Tarndale Gully, left of each image) and an unnamed series of linear gullies (upper right of each image) as at 1939 (pasture), in 1988 (16 years after planting *P. radiata* and *Pseudosuga menziesii* (Douglas fir)), and in 2017. Note, the regrowth of indigenous, early-colonising shrubland species (light green in the 2017 image) along the lower slopes, the gully floor and alluvial fans.

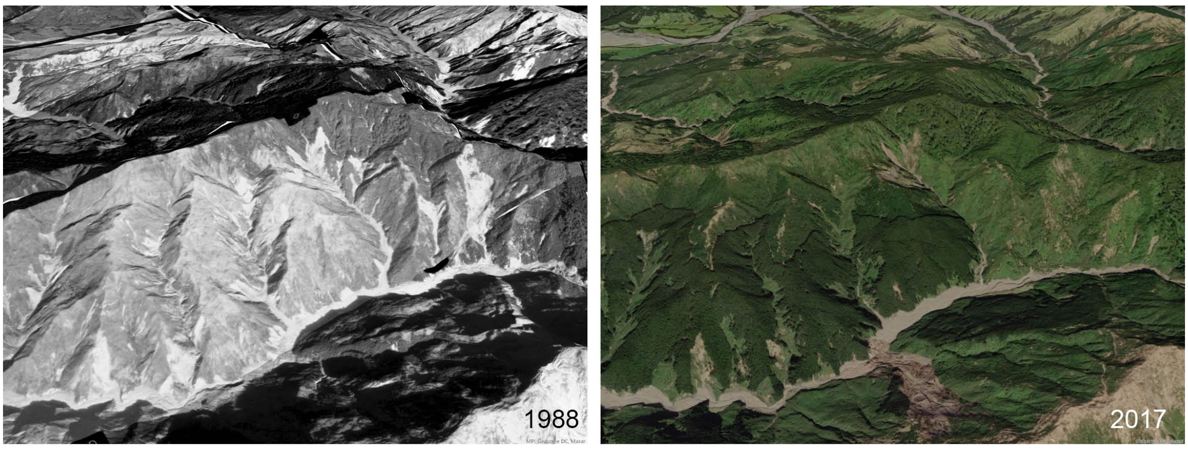

FIGURE 7: Part of the Waiorongomai catchment showing the extent of erosion within linear gullies following Cyclone Bola (1988) (left). Note the presence of indigenous, early-colonising shrubland (light green in the 2017 image) within previously eroding parts of each gully. Regrowth of indigenous shrubland has occurred since the planting of the uppermost and more stable slopes surrounding these gullies with *P. radiata* in 1998. Photography courtesy of Malcolm Penn, Ministry for Primary Industries).

of exotic woody debris and reduce sediment volumes delivered to stream channels to near natural background levels. Such a strategy would be most effective for linear gullies within the steeper and more incised Tertiary terrain and for the smaller of the amphitheatre-shaped gullies (<10 ha). Conversely, for gullies >10 ha in size, but nonetheless a likely candidate for a vegetative remediation option, an alternative strategy will be required. With greater longer-term benefits in mind this would require the entire gully watershed to be retired to allow passive (natural recolonisation) and/or managed reversion (i.e., involving supplementary seeding or planting of indigenous species) to a permanent forest cover. Additional benefits would include a reduction in the mobilisation and delivery of sediment and exotic woody debris from gullies.

Whether setbacks are established through plan rules, consent conditions or by voluntary means, they are required to be maintained (Ministry for Primary Industries 2018), thus as regenerating shrubland species will eventually be replaced by successional podocarp and hardwood forest species, the goal is that in-stream freshwater ecosystem communities, water quality and overall stream health conditions will eventually return to that akin to native forest streams (Parkyn et al. 2006).

A similar strategy should be adopted for those gullies currently planted in exotic pine but have failed to stabilise before being harvested, and where successive planting and harvesting cycles at ~27- to 30-year intervals are more likely to result in an increase in gully activity and their probable expansion. While shrubland reversion will take longer to restore full stability to these problematic gullies, the probability of a successful outcome will be greater in the longer term.

A potential adverse effect during the transitioning of gullies planted in exotic pines to an indigenous cover will be the spread of wildling pines that requires similar management to afforestation (Ministry for Primary Industries 2018). Nonetheless, a proactive approach towards identifying all potential site-specific risks in the planning and undertaking of forestry activities in and around actively eroding gullies would, in the longer term, undoubtedly minimise the risk of increasing downstream flooding and the potential off-site impacts of sediment and woody debris on regional infrastructure, personal property, and freshwater and marine ecosystems.

Neither strategy would be effective in stabilising the very active 'badass' gullies (e.g., Tarndale Gully in Fig. 6). Here, exceedingly steep headwall areas have proven to be unplantable and therefore continue to generate and deliver excessive volumes of sediment to an actively aggrading channel, thereby limiting the potential development of an indigenous vegetation cover and/or riparian buffer. Given their remoteness, the cost of hard engineering solutions (e.g., construction of concrete or earth retention dams) is neither practical nor economically viable and given that previous attempts at bioengineering solutions have failed, these gullies will probably be left to run their course.

Conclusions

This study has updated (as at 2017) earlier inventories of the spatial distribution of gullies present within the East Coast region, North Island, New Zealand, and has identified key factors that contributed to the success and/or failure of different vegetative treatment strategies aimed at ameliorating gully erosion over a 60-year period. A key finding is that given the size range, severity, and extent of gullies, and the importance of deep-seated mass movement processes associated with gully development, blanket reforestation with fast-growing, exotic species, predominantly *P. radiata*, affords the quickest means and greatest probability of successfully remediating gullies <10 ha in size. Also, remediation of these gullies occurred quickest where the surrounding watershed and the gully itself are either treated simultaneously or staged by delaying the planting of the more active parts of gullies until a noticeable reduction in runoff and sediment supply has occurred.

While other treatment options, including the establishment of poplar and/or willow poles, often in association with reverting shrubland species, has proven effective in stabilising the smaller (<2 ha) gullies, successes were countered by the initiation of numerous new gullies during localised storms and the enlargement of gullies that remained untreated, part-treated, or where treatment had failed. Many of these gullies occurred on land retained in pastoral use where the identification and treatment of sites of potential gully development is as important as the treatment of existing gullies.

The substantial investment over 60 years to retire and replant ~155 000 ha of pastoral hill country in exotic forest and an additional ~4000 ha for passive and /or managed transition to indigenous shrubland succeeded in stabilising 45% of the gullies present before rehabilitation efforts began in earnest. However, the land area currently affected by gullies is only 5% less than that before remediation treatments began, a period during which the initiation and development of gullies outstripped the ability of government, regional and territorial authorities, and landowners to fully implement designated erosion control targets by 2020-22 as mandated in their respective policy documents. This modest level of success is symptomatic of policies that have failed to acknowledge that the key to addressing multiple on- and off-site impacts of erosion will require the completion of unfulfilled targets set for the East Coast Forestry Project (ECFP), for land designated as LO3A in the Gisborne District Council's Combined Regional and District Plan, and for the project entitled 'Restoration of the Waiapu Catchment'. In the interim, the non-compliance by some landowners of their regulatory requirement to have established an effective tree cover on LO3A by 2021, and the non-enforcement of these regulations will ultimately see the initiation of new gullies and the expansion of existing untreated gullies, the rate of which will probably be determined by the frequency, magnitude, and extent of future storms. Further afforestation (exotic & indigenous) of many of the larger gullies located within LO3A, particularly within the Cretaceous terrain and Waiapu catchment, is inevitable. Of importance will be the planning and establishment of wide riparian buffers or set-back zones especially for those gullies likely destined to be planted in exotic species with the view to harvesting.

Future erosion-control funding should focus on treating as many of the 741 gullies that remain actively eroding within remaining areas of pastoral hill country of which 426 occur in areas designated as LO3A, new gullies as they form, and the future-proofing of incipient drainage channels to prevent potential gully initiation and development. Prevention is significantly more effective and cheaper than cure. Consideration should also be given to transitioning the most actively eroding gullies currently located within the exotic forest estate to a permanent indigenous vegetation cover, post-harvest.

Without these actions, gullies will remain the single largest source of new sediment and a significant contributory factor in the worsening of environmental, economic, cultural, and social outcomes for the East Coast region, particularly in the Waiapu catchment, well into the future.

Endnotes

[1] https://www.pce.parliament.nz/media/1546/sustainable-management-and-the-east-coast-forestry-project-dec-1994-small.pdf (Accessed 14 February 2022),

[2] https://niwa.co.nz/sites/niwa.co.nz/files/GDC-HBRC%20climate%20change%20report%202020_Final-compressed.pdf (Accessed 14 February 2022),

[3] https://www.nzherald.co.nz/nz/raukumara-conservation-park-our-dying-forest-and-the-community-mission-to-bring-it-back-to-life/N3DUGN3GFX77OZFQ6KNJRPUVJQ/ (Accessed 14 February 2022),

[4] https://www.nzgeo.com/stories/how-to-fix-the-raukumara/ (Accessed 14 February 2022).

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Abbreviations

ECFP: East Coast Forestry Project
ESRI: Environmental Systems Research Institute
GIS: Geographic Information System
LINZ: Land Information New Zealand
LO3A: Land Overlay 3A
NES-PF: National Environmental Standard for Plantation Forestry

Competing interests

The authors declare they have no competing interests.

Authors' contributions

MM initiated this project and is the primary author. AS digitised the gullies and compiled the data into spreadsheets. Both authors read and approved the manuscript.

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Availability of data and materials

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Ethics approval and consent to participate

Not applicable.

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