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Monitoring and reporting of whole farm plans as a tool for affecting land use change

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Abstract

Following the major storm in Manawatu/Rangitikei in February 2004, Horizons Regional Council developed the Sustainable Land Use Initiative (SLUI) which aims to address and implement effective programmes for controlling the region's soil erosion. A key component of SLUI is preparing 1,500 whole farm plans (WFPs) over 10 years, with 50% of them on the most at risk, highly erodible land. Monitoring the environmental benefit of the implementation of each WFP is critical for determining progress towards defined targets across each farm over time and achieving progress at the catchment scale. Current monitoring activities and future plans of four regional councils (Horizons, Greater Wellington, Hawke's Bay, and Taranaki) were surveyed and are reported. Attributes of vegetation at sites within a farm that should be recorded and/or monitored are type (exotic forestry, spaced trees, indigenous scrub/forestry), age, area, canopy cover, and trunk diameter (at least for spaced trees). It is recommended that selected attributes e.g. canopy cover, trunk diameter be monitored every 3-5 years until their rate of change declines considerably. Data should be collected by the land manager in conjunction with the land owner to facilitate information sharing and developing a closer association between the parties. A simple model that links vegetation type/landuse at the farm scale with sediment export off-farm has been developed. This provides a framework for quantitative assessment of effectiveness of conservation works, but needs to be field-tested for applicability across a range of farms and in catchments with different characteristics.

1. Introduction

Horizons Regional Council is the lead agency for the Sustainable Land Use Initiative (SLUI), which is a regional initiative born out of the February 2004 storm event. SLUI aims to reduce the region's reliance on government relief/recovery assistance in the future, protect hill country and lowland communities and assets from future storm events and the ongoing impacts of the 2004 storm event, and protect the soil asset upon which our rural economy is based. Key components of the initiative include an update of land resource information, development and delivery of whole farm plans (WFPs), capacity building, and monitoring and reporting on progress. The development of individual WFPs incorporating physical, farm management and business plans to achieve environmental and economic sustainable land use, is a key mechanism for delivering future-proofing assistance to the region's land owners. The target is 1,500 plans over 10 years with 50% of plans on the most 'at risk' landscapes to erosion. Whole farm plans requested in priority areas are being given priority.

An effective on-farm monitoring programme is essential and must be useful at measuring and analysing progress at both the farm and broader scales. It will need to provide information to the landowner for decision making and also be suitable for scaling up to the catchment scale. Monitoring to date of the effectiveness of WFPs has been largely limited to monitoring implementation of the conservation works programme, an activity based approach. Shifting the emphasis from actions/tasks to environmental outcomes will provide council with direct measures of the achievements towards the target goals of land stabilisation, retention of soil on farm, reduced sediment loading, less damage to infrastructure from slips, and reduced flooding. It will also indicate the rate at which progress is being made towards these goals, both at the farm and catchment scales, through appropriate amalgamation of data from several or many farms.

This report documents a set of guidelines to assist in the development and implementation of a customised monitoring programme for an individual WFP. This will ensure that the information collected is appropriate for that farm, and useful for scaling up beyond the farm boundary. This will enable the generation of a robust dataset in terms of environmental monitoring at a range of scales. This represents a significant change in approach to the current monitoring programmes completed as a part of a farm plan.

In this report, current monitoring techniques and aims are reviewed before developing monitoring guidelines and an approach to determine overall effectiveness of all conservation works in a WFP, in terms of sediment discharge off-farm. Horizons Regional Council initiated this project, but adjacent councils with significant areas of hill country in their administrative regions were consulted because of the general relevance and applicability of the project. A brief overview is presented on a current Foundation for Research, Science and Technology (FRST)-funded research project to determine the effectiveness of spaced conservation trees during recent storms in Manawatu and Wairarapa. The project involves quantitative measurement of attributes of individual trees in the field and provides more comprehensive information on tree size than can be provided by tree age alone. One or more attributes may be appropriate for routine monitoring of spaced plantings over time.

2. Current monitoring methods used by Regional Councils and future plans

An overview of the project, including a handout (Appendix 1), was presented to participants at the annual meeting of the Willow and Poplar Research Collective (WPRC) on 31 July 2007 at HortResearch, Palmerston North. This was attended by staff of Greater Wellington, Hawke's Bay, Horizons, Environment Bay of Plenty, and Taranaki Regional Councils. Brief feedback was received from several of the participants during the meeting. In August, staff of Greater Wellington, Hawke's Bay, Horizons, and Taranaki Regional Councils were interviewed in their offices to obtain more information on approaches and plans. The staff interviewed were different from those who attended the WPRC meeting, except for Taranaki Regional Council where the person interviewed also attended the earlier meeting. Regional council staff who contributed comments are listed in Appendix 2. A summary of the feedback and discussions follows, and is presented for each council under the headings of 1) WPRC meeting and 2) Office. Additional information is provided to more fully document the extent of the feedback, specifically on monitoring, and in the wider context e.g. rationale and purpose of farm plans.

2.1 Greater Wellington Regional Council

WPRC meeting: Council conducts farm planning in the region and at least 30% subsidies are available for these; some flexibility in subsidy is available. An objective is to establish 200 ha of forest woodlots/yr and 400 ha of poplar and willow plantings/yr. It is desired to have a targeted and consistent approach to sustainable land use at local, regional and national government levels.

Office: Council produces two types of farm plans for land owners:

1) Conservation Plan, usually at 1:10,000 scale; 10 yr erosion control plan, then reviewed every 10 years, have 30% contribution of rates to works, land management officer meets annually with landowner to discuss programme.
2) Sustainability Plan, which is more detailed than a Conservation Plan, is a 30-yr vision of the property's requirements, has physical description, farm production (e.g. livestock, woodlot assets, spaced tree plantings), land assessment (e.g. landform types, LUC information), pasture DM production for landforms/LUC units, and uses the Agroforestry Estate Model (AEM) around woodlot options/scenarios on farms. These plans get 40% contribution of rates to works.

Both plans, particularly the Sustainability Plan, are focussed on areas with the highest erosion. About 500 plans have been made for relevant farms in the region since the 1950s. There is currently a core of about 300 farm plans mainly because some plans have ceased, council staff have left, and farms have changed ownership. Of these, there are about 275 Conservation Plans and 25 Sustainability Plans. About 25 Sustainability Plans have been prepared in the last ten years. Nearly all plans have been prepared as a result of farmer approaches, although for some Sustainability Plans, initial approaches to farmers have had to be made to gain interest and acceptance of the concept.

Various features of individual conservation works are monitored routinely including number of poles and land areas planted, but there has been little attempt to monitor their direct effectiveness in terms of key environmental outcomes.

The effect of soil conservation tree plantings on reducing damage sustained by the Whareama catchment during the storm of 8-11 April 1991 was assessed (Hicks, 1991). Planting categories included space planting, close planting, and species e.g. poplar, willow, pine, and acacia, and plantings were assessed as 'adequate' or 'inadequate' for their potential capability for controlling erosion on inspected sites. More recently, council contracted a region-wide assessment using the point-sample survey method of soil intactness developed by Dr D. Hicks (Crippen and Hicks, 2004). This was conducted for the council's statutory requirement for state of the environment reporting for the region. The technique, or variants of it, has been used in several recent surveys by some other regional councils e.g. Auckland, Environment Waikato, and Horizons, and is being documented by the National Land Monitoring Forum (national group of regional council scientists and officers) as part of its point sampling manual, which is expected to be released shortly. The method involves a grid overlay of sites on aerial photographs, with geo-referencing, which can be used for single assessments, or repeat assessments at various time intervals. Council will repeat the 2004 assessment in 2009.

2.2 Hawke's Bay Regional Council

WPRC meeting: The council aims to maintain the productive capability of the region's resources and it has quite a lot of information on how effective conservation works have been, although good examples of this and how effectiveness was assessed, were not provided. Quite often, vegetative conservation works are assumed to be effective if the vegetation is alive and healthy, and the extent of erosion of the planted site has not changed appreciably. Farm plans have been used for many years, but they should not be regarded as the be all and end all of activities at the farm level. They are only produced for farmers who want them.

Office: The purpose of farm plans is primarily sediment control (reducing sediment loss), reducing nutrient runoff, enhancing biodiversity, and improving (at least maintaining) farm profitability. Land use and intensity have different impacts on surface soil e.g. bull beef affecting soil compaction. The trigger points at which erosion occurs are highly variable. For example, quite massive earthflows are spectacular but they can contribute negligible sediment loadings to streams. There is uncertainty about the sediment contributions of different erosion forms/types. Council has advocated gully control through pair planting and thinks it works well, but it does not have any quantitative measures.

Council has an environmental management group, and a Land Monitoring Strategy (LMS) was prepared in December 2006 for a 5-yr term: 2006-2011 (Phillips 2006). There is a statutory responsibility to monitor land in the region, and the LMS outlines a framework and methodology to address this. The council plans to monitor the extent of erosion on hill country (and other land) throughout the region over the long term. For hill country, council has committed to using Dr Hicks' aerial photo based point-sample methodology for soil intactness (Section 2.1) as soon as practicable. It is possible that another erosion monitoring technique(s) could be developed if high-resolution satellite imagery (resolution of 0.6 m) becomes available for region-wide, routine use.

The status of land in Hawke's Bay was assessed by council in 1997 and 2005 using an attribute termed Sustainable Land Use (SLU). This is derived from overlaying land cover information from the Land Cover Database (LCDB – versions 1 (1996/97) and 2 (2005)) with a range of acceptable land uses from the Land Use Capability classification/NZ Land Resource Inventory. The SLU indicator will likely continue to be used about every five years or as updates of the LCDB are released because it will provide a regional overview of changes in vegetation/land use type e.g. exotic forestry, pastoralism, and retirement. The region-wide assessments are complemented with detailed land use surveys in some areas (including detailed field reconnaissance by council staff), particularly the intensively used plains. However the approach is not generally applicable at the conservation works scale within a farm boundary because the imagery used has insufficient resolution e.g. to detect spaced plantings of poplar and willow. Refinement and usefulness of the approach may occur if high-resolution satellite imagery becomes available. There are plans to provide this through Local Government NZ over the whole country but timeframes for availability are uncertain.

Council has not considered monitoring the effectiveness of individual conservation works within a farm, but sees potential value of such an approach for prioritising works. Quantification of the environmental benefits/outcomes of individual works would be useful. Suggestions would be welcome on monitoring at this detailed scale e.g. what, where, when, and how.

2.3 Horizons Regional Council

WPRC meeting: SLUI is a significant initiative for council and targets erodible land throughout the region. The number of WFPs being produced is large and ambitious. There are grants for this work but land managers have a little flexibility in how this money is allocated. Interest was expressed in ways to determine the effectiveness of individual conservations works on a farm and how this could be linked with sediment distribution (on- and off-farm).

Office: There are a number of ways to monitor effectiveness of conservation plantings, and there is good support in principle for using a quantitative erosion model (Schierlitz *et al.*, 2006) to predict sediment contributions from catchments. The most comprehensive report on the effectiveness of soil conservation works in the region was conducted in the early 1990s (Hicks *et al.*, 1993) using methodology similar to that used in the survey of damage experienced in the Whareama catchment in Wairarapa in 1991 (Hicks, 1991).

An assessment of erosion and vegetation cover, involving interpretation of aerial and satellite imagery, was conducted following the February 2004 storm (Hicks and Crippen 2004). Vegetation was classified into 14 categories (open pasture, pasture with scattered scrub (exotic or natural), pasture with extensive scrub (exotic or natural), pasture with scattered trees (exotic or natural), pasture with extensive trees (exotic or natural), scrub (exotic or natural), trees (exotic or natural), and other vegetation) and the landscape was classified into eight landforms. Assessment sites were chosen at random, but the approach was otherwise similar to Dr Hicks' point-sample survey of soil intactness (Section 2.1). Horizons Regional Council conducted the first use of this survey method (Crippen, 1999).

Interpreting imagery with respect to vegetation type and erosion extent/severity beneath has been the main method of determining the effectiveness of vegetation by Horizons and other councils. There has been negligible quantification of the characteristics of the vegetation e.g. height, canopy dimensions, trunk diameter, or little attempt to link vegetation cover/characteristics to sediment contribution in a quantitative way. Such approaches would be useful to council.

There are two main objectives with Horizon's current initiative:

1. Reduce sediment loss from farms and damage to rural infrastructure e.g. roads.; and
2. Reduce damage at next and subsequent storms, and hence damage to infrastructure on-farm (tracks, buildings, fences);

If sediment is lost from hillsides, perhaps it might be retained mostly on the farm if there are appropriate structures e.g. dams, or biological habitats e.g. wetlands, where main farm losses might occur.

The effectiveness of conservation works at the farm and individual site level has been considered, including how resources should be distributed within the farm, and how effectiveness of individual works might be judged. Negligible research on this subject has been conducted. As with Hawke's Bay Regional Council, there are questions about the sediment contribution from different erosion types, but also different erosion severities and different works options for those. An example mentioned was sediment in-filled gullies which get pugged and suffer sheet erosion from hoof action and rain. Is it better to plant poplars in the gully to dry it out or to retire it? Alternatively, is it better to concentrate on other parts of the farm?

Subsequent comment: In the late 1990s, Regional Councils and Ministry for the Environment agreed that the indicators for hill country erosion were twofold; the pressure indicator being land use in relation to land use capability and the state indicator being soil intactness. Most if not all regional councils use these indicators, although there are minor variations in how they are measured from council to council. Measurement of the indicators is slowly becoming more and more consistent between councils.

2.4 Taranaki Regional Council

WPRC meeting: Council has conducted farm plans for a number of years and has considerable experience in their preparation. Money is not available for subsidies etc. Farmers have plans prepared for free, they receive a high quality document, and the council land manager has a chance to develop a good relationship with each farmer. Council monitors outputs at the farm level e.g. where poles are planted. It does not have a process for monitoring the effectiveness of the works, but has an interest in the project and in identifying ways to monitor effectiveness/environmental outcomes.

Whole farm plans are worthwhile and there was support for the approach Horizons Regional Council has taken in targeting highly erodible land. Investment of resources should be less of a priority for more stable land because it is not potentially important in contributing sediment within and off-farm. There was interest in the proposed linking of conservation works across an individual farm to sediment distribution, and ways to monitor changes spatially and over time.

Office: Council has a Regional Soil Plan for Taranaki (2001) to assist it in conducting its soil conservation function under the Resource Management Act. The plan became operative in October 2001 and will be reviewed fully in 10 years. It includes the implementation of the Sustainable Land Management Programme (SLMP) which targets 50% (or 143,000 ha) of the hill country in private ownership to be subjected to the programme over 10 years, so approx. 15,000 ha/yr. The target of 15,000 ha/yr varies depending on staff levels and what is realistic with resources. For example, in 2005-06, farm plans were prepared for 11,737 ha while 15,000 ha were achieved in 2006-07. Council promotes the full suite of land management activities including farm plans.

In the 1990s, there was a focus on forestry plantings and management, use of the Agroforestry Estate Model (AEM) etc., but the focus changed with the downturn in the forestry industry. Up until about 1996, landform types were classified on a slope system based on MAF erosion/pasture production trial work e.g. pasture production was estimated on different landforms/slope classes, and AEM was used to integrate forestry into farming. The current system uses the Land Use Capability (LUC) classification as its baseline. There is interest in the redistribution of resources/effort within a farm to maintain current revenue or even increase revenue when marginal land is taken out of pasture production.

Traditional soil conservation measures are recommended in the farm plan for the entire property. The works programmes for farm plans used to be prepared and costed for the whole property but the costings became outdated too quickly. There is now greater use of a 2 or 3 year timeframe for costings which are adjusted during the annual discussion with the farmer about the plan specific to their property. Plans include stock performance (types, numbers, ages etc.) and carrying capacity, and pasture production, so that financial implications can be calculated using current information. Stock and pasture data presented in plans can be used to compare between years and hence determine changes.

Farm plans prepared by this council typically have an overview of the farm, its physical resources, proposed and/or recommended works programme etc. Council offers four types of property plans: comprehensive farm plans, agroforestry plans, conservation plans, and riparian plans. The SLMP aims to improve the physical (and financial) status of land by working with interested land users to address accelerated erosion problems. It is proposed that 70% of properties in the SLMP implement their plans in whole or in part within the timeframe of the Regional Soil Plan.

This Plan is up for mid-term review this year. Through implementation of the Regional Soil Plan (through SLMP), council aims to achieve an increase of 50% in the area covered by production forestry and soil conservation planting on LUC Classes 6e and 7e privately-owned land in the hill country over a 10-yr period.

Changes in land use/vegetation are monitored as part of the Regional Soil Plan through the State of the Environment Monitoring Programme and through the established sustainable land use monitoring programme. This involves the analysis of aerial photographs on 25 hill country sites – taken in 1993 and analysed in 1995, to form baseline data – and then analysing subsequent photography to detect change. Also, there is annual interaction with farmers who have plans, so that changes can be detected at that level. A range of information on the implementation of the SLMP is available e.g. number of requests for plans, number of property plans produced, the area they cover in terms of land area and area of LUC classification units, activity reports, and extent of implementation of plans by landowners. Some of this information is useful for monitoring vegetation/land use change, but it does not assess the environmental benefit of the vegetation or the changes.

2.5 Summary

Councils consulted have techniques to determine the distribution of vegetation types (land uses) across landscapes and their changes spatially and temporally. These are largely based on interpretation of aerial and satellite imagery and are expected to be a core part of continuing surveys, particularly at regional level. The techniques can be used at any scale (farm, district, catchment etc.) depending on the availability of imagery of appropriate resolution and land coverage. Several assessments have been conducted on the effectiveness of conservation works in reducing the extent and severity of erosion during storm events and their implications for sediment delivery. Consequently, a lot of institutional knowledge and experience exists.

Conservation works on farms have been monitored routinely with respect to the areas (ha and % of farm) and classes of land planted, species and clone planted, and the number of poles planted and when. This provides a baseline when works started and additions over time. There has been negligible quantitative monitoring of individual works post-planting in terms of tree size and likely contribution of vegetation types to sediment control/loss. A method for monitoring the environmental effectiveness of conservation works at the farm scale, across the property and over time, is desirable. It is potentially very useful for prioritising where and when conservation works are implemented.

3. Effectiveness of wide-spaced conservation trees - current research

A study is being conducted to determine the effectiveness of spaced plantings of poplar, willow and *Eucalyptus* spp. in reducing soil slippage during recent storms in Manawatu and Wairarapa. It is funded by FRST through their SLURI programme and is being undertaken by AgResearch and HortResearch, in collaboration with Horizons and Greater Wellington Regional Councils. Data have been collected on 5-10 trees at each of 65 sites in Manawatu (40 sites) and Wairarapa (25 sites). Sites were selected from aerial photographs of areas/farms known to have been damaged during storms in February 2004 (Manawatu) and July 2006 (Wairarapa).

At each site, distances between the 5-10 trees were measured and trees were measured for diameter at breast height (dbh; 1.4 m above ground on the upslope side of trees), height, and radius of the canopy in four directions perpendicular to each other. Aspect of the site and slope within 1-3 m of each tree were recorded. The area of fresh erosion (exposed slip scars) at each site was mapped and included in computer-prepared diagrams showing layout at each site. The areas (m^2) of circles of 10 m radius, centred on each measured tree, have been calculated and total area per site calculated. A radius of 10 m was chosen because most of the coarse root (> 2 mm diameter) mass and length of at least young (< 13 years; dbh < 30 cm) individual poplar trees on slopes is within this range e.g. McIvor *et al.* (2008). Relationships have been developed (n=6 from McIvor *et al.* (2008) and unpubl. data) between root mass and dbh, and between root length and dbh, as follows:

Log_{10} structural root mass = 3.62 * log_{10} DBH – 3.52 (R^2 = 0.95)

Log_{10} structural root length = 2.26 * log_{10} DBH – 0.18 (R^2 = 0.93)

These relationships show the benefit of measuring dbh of trees because it can be used to estimate root attributes, and measurement of dbh in the field is quick and easy. The study of McIvor *et al.* (2008) also determined the lateral and vertical distribution of roots of trees aged 5 yrs (dbh = 8.4 cm), 7 yrs (14.0 cm) and 9.5 yrs (21.3 cm), with the lateral distribution shown in Figure 1. Additional information on the trees – above- and below-ground - is presented in Table 1.

Table 1. Dimensions of excavated 'Veronese' poplars together with relationships between trunk dimensions and mass (excluding root crown) and length of roots >2 mm diameter, for trees of three ages growing on hill country near Palmerston North.

Tree age (yr)	Height (m)	DBH (cm)	Trunk cross-sectional area (cm^2)	Root length (m)	Root mass (kg DM)	Root mass: trunk area	Root length: trunk area
5	7.3	8.4	55.4	79.4	0.57	0.010	1.43
7	9.0	14.0	153.9	349.3	7.80	0.051	2.26
9.5	13.3	21.3	356.1	663.5	17.90	0.050	1.87

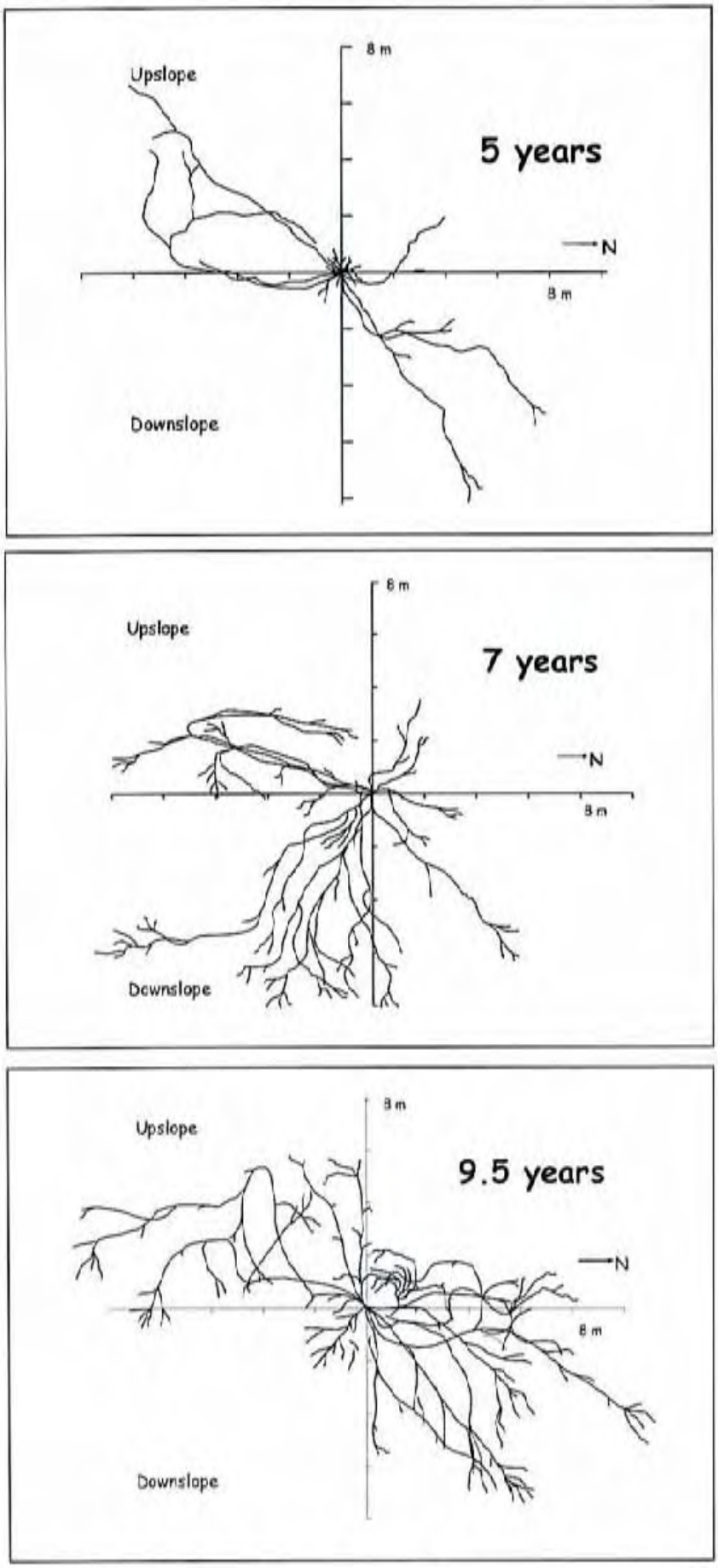


Figure 1. Lateral distribution of roots > 2 mm diameter of 'Veronese' poplar trees aged 5, 7 and 9.5 years growing on hill country near Palmerston North.

4. Overview of erosion model: NZeem®

The erosion model is described in Appendix 3.

5. Approach for monitoring effectiveness of conservation plantings on a farm

5.1 Attributes to monitor

Attributes that should be assessed or measured in the implementation of the works programme in a WFP are: (i) vegetation type and canopy cover (extent); (ii) the area of each works (at the individual site level); and (iii) age of vegetation.

These can all be assessed using aerial photography at an appropriate scale e.g. 1:3000 or (preferably) higher resolution, complemented with planting plans describing location and timing, and other knowledge of the farmer/land manager. Detecting areas of forestry, whether exotic or indigenous, is easier than for those with spaced plantings of conservation trees on pasture, particularly when the trees are young, and field checking of sites is recommended e.g. for survival. Also, tree growth of the same species/clone can vary considerably with aspect, position on a slope, and other factors, so that knowledge of tree age is only a preliminary indication of the likely size of trees.

For conservation works involving forestry (exotic or indigenous), canopy cover can be estimated from appropriate aerial photographs, but a sequence over time (e.g. every 3-5 years) is required to make this a particularly useful approach to determine critical times when effectiveness for erosion control (and sediment reduction) is increased significantly (e.g. at canopy closure). Estimates of canopy cover per site with an accuracy of plus or minus 10% should be more than adequate to describe canopy development over time. Sites with spaced trees on slopes or in gullies are more difficult to assess for canopy cover because they almost always have lower and more variable tree densities than forestry. It is unwise to compare canopy covers of forestry with those of spaced trees because the same canopy cover in both vegetation systems will usually not indicate the same stand density - hence the implications for root distribution patterns and erosion control potential are quite different.

For spaced trees, it is recommended that at least one measurement of tree size – dbh – is measured on a sample of trees at an individual site e.g. 1-5% of them, to complement data on tree age. This might be conducted on the same trees once every 3-5 years until tree maturity so that the task does not become overly onerous. Collection of such data will be useful to define tree size and will enable a better description of the status of trees which survive or die during future storms, and those which hold or fail to hold soil on eroded slopes. Collection of data by the land manager along with the land owner will create the opportunity to strengthen the association between them.

In the absence of appropriate photography (resolution and times), visual estimation of canopy cover of forestry (indigenous and exotic) at sites within a farm could be conducted during site inspections using a stratified scale e.g. increments of 20% from 0 to 100% every 3-5 years. An idealised representation of different proportions of canopy cover is shown In Figure 2.

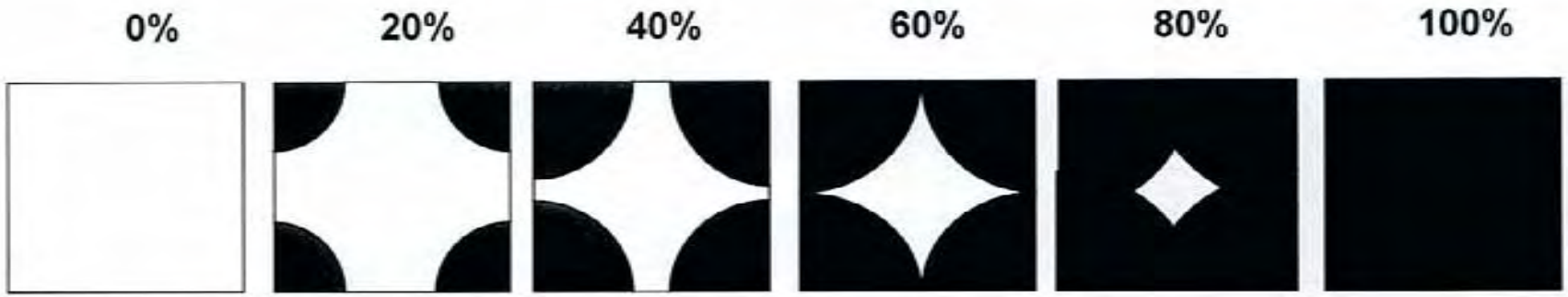


Figure 2. Simulated canopy cover provided by four evenly-spaced trees (each centred on a corner of a square) as they grow from seedlings in open pasture (0% cover) to trees interacting significantly with neighbouring trees to produce a closed canopy (100%).

5.2 Vegetation types and quantification of extent of maturity

For a planting programme in any Farm Plan, there will be recommendations for one or a mix (usually) of mutually exclusive land uses/conservation works of

(i) Exotic forestry
(ii) Spaced trees on pasture (2-tier farming, agroforestry, tree-pasture system)
(iii) Indigenous forestry (retired from pasture).

At the start of the planting programme, there may be any combination of these 1 – 3 vegetation types growing at multiple sites within the farm. As the programme is implemented, the proportion of the total area of the whole farm covered by the vegetation types will change. For comparison and to estimate improvement over time as a result of the planting programme, an inventory of vegetation before planting is required. Key attributes of vegetation to assess as the planting programme is implemented, including those from Section 5.1, are shown in Table 2. These data can then be used to calculate some of the attributes described in subsequent sections e.g. maturity factors, ultimately enabling estimation of sediment discharges.

5.2.1 Exotic forestry

Close-tree planting (Figure 3) will reduce erosion on pastoral areas by 90% once it is mature (Dymond *et al.*, 2006). For trees less than 20 years old, a maturity factor can be calculated by

$M_f = Age_f / 20$

where M_f is the maturity factor of forestry, and
Age_f is the age of the trees in years (for trees older than 20 years M_f is set to 1).

The long-term mean erosion rate is reduced by M_f x 0.9.

Figure 3. Mature forest of *Pinus radiata* with developing indigenous forestry in upper background (left photo), and seedlings of *Pinus radiata* aged < 3 years (right photo).

Table 2. Vegetation cover on a farm with a whole farm plan (WFP): Essential and supporting data for estimating sediment export from farm. (It is strongly recommended that these data are collected in consultation with the land owner.)

Total highly erodible land (HEL) on farm (ha)[#] _____

Total farm area (ha) _____

A) EXISTING VEGETATION (before implementation of planting programme in WFP)

	Site no. *	Planting/retirement date	Area (ha)	Age (yrs)	Canopy cover (%) ^	DBH (cm)	Tree extent (%) >
Indigenous scrub/forestry	1						
	2						
	3						
	n						
Total farm covered (ha)							
Proportion of total farm area (%)							
Exotic forestry	1						
	2						
	3						
	n						
Total farm covered (ha)							
Proportion of total farm area (%)							
Spaced trees	1						
	2						
	3						
	n						
Total farm covered (ha)							
Proportion of total farm area (%)							

B) PROPOSED VEGETATION (implementation of planting programme in WFP over time)

	Site no.	Planting/retirement date	Area (ha)	Age (yrs)	Canopy cover (%)	DBH (cm)	Tree extent (%) >
Indigenous scrub/forestry	1						
	2						
	3						
	n						
Total farm treated (ha)							
Proportion of total farm area (%)							
Exotic forestry	1						
	2						
	3						
	n						
Total farm treated (ha)							
Proportion of total farm area (%)							
Spaced trees	1						
	2						
	3						
	n						
Total farm treated (ha)							
Proportion of total farm area (%)							

N.B. Coloured cells indicate minimum recommended data to collect

predicted from erosion model based on information collected at 1:50 000 scale (Dymond and Shepherd, 2006)

* site number ranges from 1 to n where n=maximum number of sites.

^ assessed from aerial photographs and/or on-site assessment

> proportion of trees in WFP that have been planted, have survived and that are well maintained.

5.2.2 Spaced trees on pasture

Spaced tree plantings (plantings on slopes (Figure 4) and gully-tree plantings) will reduce mass-movement erosion by 70% once plantings are mature ((Hawley and Dymond, 1988; Thompson and Luckman, 1993; Hicks, 1995).

Figure 4. Spaced trees of *Populus* spp. aged 10-15 years growing on slopes in the lower North Island.

The maturity factor of the soil conservation works can be calculated by

$$M_p = f \times Age_p / 15$$

where M_p is maturity factor of the soil conservation trees,
f is the proportion of trees in the plan that have actually been planted, have survived, and are well maintained, and
Age_p is the age of the soil conservation trees (for trees older than 15 years Age_p is set to 15).

The long-term mean erosion rate is reduced by M_p x 0.7.

5.2.3 Indigenous forestry (retired from pasture)

Vegetation on retired land is assumed to be at one of five phases with maturity factor M_r:

(i) reverting pasture; $M_r = 0.0$
(ii) incomplete scrub canopy closure (early stage); $M_r = 0.1$
(iii) incomplete scrub canopy closure (intermediate stage e.g. 3 years); $M_r = 0.5$
(iv) complete scrub canopy closure; $M_r = 0.9$ (usually after 5 years), and
(v) indigenous forest. $M_r = 1.0$

The long-term mean erosion rate is reduced by M_r x 0.9.

Figure 5. Complete scrub canopy closure (left photo) and with intermediate aged *Pinus radiata* forest on upper slope (right photo).

Assessment of the above vegetation types over time, using Table 2 as a template, will provide a database containing conservation tree/forest stand age, dbh, and canopy cover. This will be valuable for determining variation in vegetation growth patterns between sites within a farm and how relationships between age and dbh, and age and canopy cover, change with time and site. A district and regional profile of vegetation performance through implementation of planting programmes in a number of WFPs will be an important extension.

5.3 Calculation of sediment export from farm

For simplicity, it is assumed that all sediment lost from eroded land enters waterways and leaves the farm. However significant quantities of sediment may be retained on-farm through appropriate structures e.g. dams, or through natural means e.g. wetlands, but these are not considered here.

(1) Sediment export (tonnes/yr) from land with **exotic forestry** is e_f x [1-M_f x 0.9] x A_f

where e_f is the mean erosion rate (tonnes/km^2/yr) of the exotic forestry land if it was in pasture (from NZeem®), and
A_f is the area of exotic forestry in the farm plan (km^2).

(2) Sediment export (tonnes/yr) from land with **spaced trees** is e_p x [1-M_p x 0.7] x A_p

where e_p is the mean erosion rate (tonnes/km^2/yr) of the pastoral land with trees, if it was in pasture only (from NZeem®), and
A_p is the area of land with trees on pasture in the farm plan (km^2).

(3) Sediment export (tonnes/yr) from land with **indigenous forestry (retired from pasture)** is e_r x [1-M_r x 0.9] x A_r

where e_r is the mean erosion rate (tonnes/km^2/yr) of the indigenous forestry land if it was in pasture (from NZeem®), and
A_r is the area of indigenous forestry in the farm plan (km^2).

e_f, e_p *and* e_r may or may not be the same.

The **total sediment export** from a farm, S (tonnes/yr), which contains land use/ conservation works with a range of maturities, may be calculated by estimating the mean maturity factors of **exotic forestry**, **spaced trees on pasture**, and **indigenous forestry (retired from pasture)**.

$$S = e_f(1-0.9\overline{M}_f)A_f + e_p(1-0.7\overline{M}_p)A_p + e_r(1-0.9\overline{M}_r)A_r$$

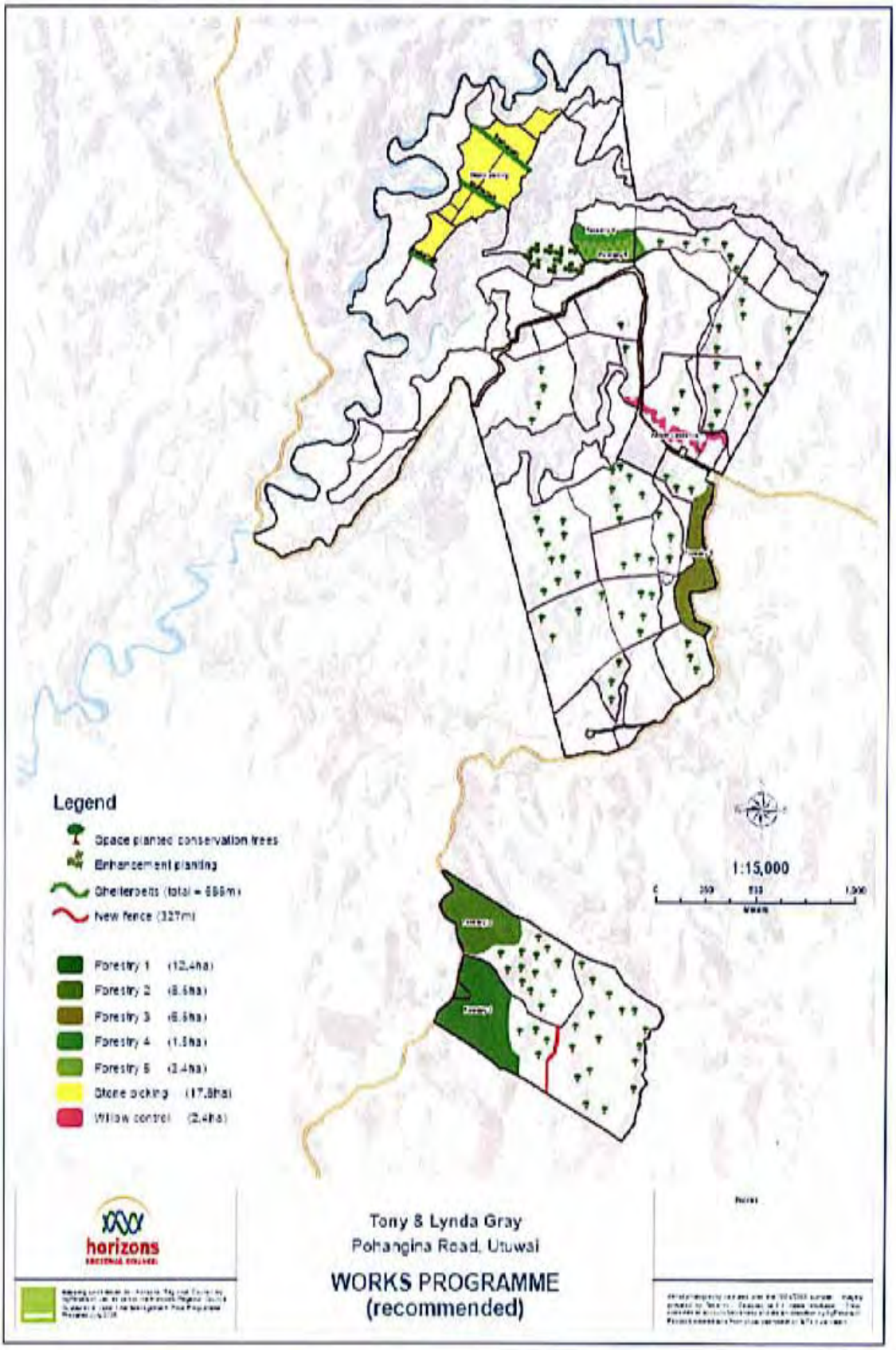
where $\overline{M}_f$ is the mean maturity factor for the exotic forestry sites, $\overline{M}_p$ is the mean maturity factor for the spaced tree sites, and $\overline{M}_r$ is the mean maturity factor for the indigenous forestry sites.

In a WFP for a 20 yr period, for example, there may be:

- 3 sites with exotic forestry planted in Yr 0, Yr 5 and Yr 15;
- 20 sites with spaced trees on pasture (annual plantings of 150 poles); and
- 2 sites where growth of indigenous vegetation is encouraged through retirement – the first in Yr 5 and the second in Yr 15.

The formula can be applied at any stage of the implementation of the conservation works in a WFP ranging from entirely new, through partial implementation, to completed implementation. Therefore it can be applied to those WFPs already implemented in Horizons Regional Council's SLUI programme.

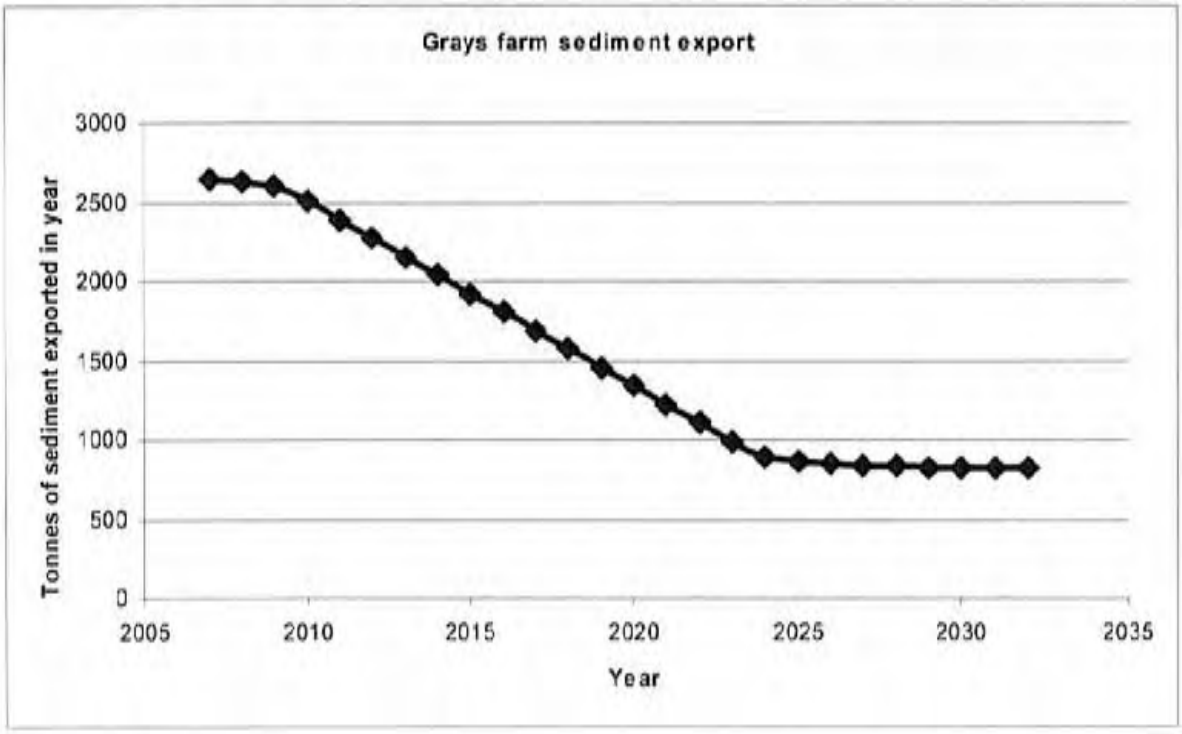
As an example, we apply these formulae to the Whole Farm Plan for the property owned by Tony and Lynda Gray in the Pohangina Valley. An overview of the recommended works programme, to be completed after 5 years, is presented in Figure 6.


Legend
Space planted conservation trees
Enhancement planting
Shelterbelts (total = 696m)
New fence (327m)
Forestry 1 (12.4ha)
Forestry 2 (8.6ha)
Forestry 3 (6.6ha)
Forestry 4 (1.8ha)
Forestry 5 (2.4ha)
Stone picking (17.8ha)
Willow control (2.4ha)
1:15,000
horizons
Tony & Lynda Gray
Pohangina Road, Utuwai
WORKS PROGRAMME
(recommended)

According to NZeem® the Grays' property currently exports 2640 tonnes of sediment per year on average. If the following soil conservation methods (from the WFP) were implemented

Year 1 - 200 space-planted poplars
Year 2 - Afforestation of 3.4 ha; 200 space-planted poplars
Year 3 - Afforestation of 8.6 ha; 130 space-planted poplars; 70 poplars for gully control
Year 4 - Afforestation of 12.0 ha;130 space-planted poplars; 70 poplars for gully control
Year 5 – Afforestation of 6.6 ha; 200 space-planted poplars.

then the sediment export from the farm would reduce gradually from 2640 tonnes/yr to 820 tonnes/yr over 20 years.



6. Conclusions and recommendations

- Monitoring of conservation works in terms of the extent of implementation e.g. number of poles planted, and areas treated, is well developed in surveyed regional councils.
- Several regional councils have a strong interest in quantifying the effectiveness of conservation works at the farm scale. There is uncertainty about the best ways to achieve this.
- Conservations works should be monitored using sequential aerial photography at appropriate scale e.g. canopy cover at 3-5 year intervals, complemented with field measurements of a sample of vegetation type. For spaced trees, it is recommended that trunk diameter be measured every 3-5 years until there is a significant decline in trunk expansion. This information will complement data on

tree age because growth of trees of the same age can vary considerably with position on slope and other factors.

- A simple model has been developed that estimates the environmental benefit of the three major vegetation covers/land uses at sites within a farm with respect to sediment export from the property. It has parameters of vegetation type/cover, vegetation age, and area of treatment. This model needs field-testing, and refinement where necessary, for applicability across a range of farms and regions with significant areas of hill country.
- Data should be collected by the land manager along with the land owner to facilitate a closer association and understanding between them.

Acknowledgements

Photographs in Figures 3-5 were supplied by Deric Charlton, except for the left photograph in Figure 4 (ex. HortResearch).

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Appendix 1: Handout to WPRC meeting on 31 July 2007.

Monitoring and reporting of whole farm plans as a tool for affecting land use change

Initiated by Horizons, Envirolink project (medium grant <$20K); will contribute to Sustainable Land Use Initiative (SLUI).

SLUI aims to increase the community's and environment's resilience to future extreme events. Major means for effecting required change will be the whole farm plan (WFP).

An effective environmental monitoring programme is essential to be able to measure and analyse the impact of the approach at both farm and broader scales. An effective monitoring programme will have to provide information to the landowner for decision making and be used for scaling up to the catchment scale. Monitoring to date of the effectiveness of WFPs has been largely limited to monitoring of the works programme. Shifting the emphasis from actions to environmental outcomes will provide council with direct measure of the achievements against the desired goal.

For example, how effective has the planting of 50 poles per year for 5 years been in reducing sediment loss from x, y, z sites on a farm, and what information should be collected through appropriate monitoring, to be better able to answer such a question?

This project aims to document a set of guidelines to assist the development and implementation of a customised monitoring programme for each individual WFP.

The key tasks are:

1. Collate information on current monitoring activities within several regional councils - scope, level of detail, frequency etc. Establish current and future approaches of regional councils to environmental monitoring in managed landscapes.
2. Develop a practical monitoring framework e.g. for vegetation management for sustaining soils. Refine in consultation with regional councils.
3. Produce report.

Some issues....

1. How should effectiveness of works be assessed? (attributes, timeframes, frequencies etc.)
2. Sediment delivery – within farm; off-farm ('connectedness').
3. Assessment of overall effectiveness of a farm e.g. 15-20 works on a farm and assess effectiveness of each works; how to arrive at an overall farm assessment (e.g. an average of effectiveness of all works, or a weight on basis of area/age of each works, or?).
4. Linking individual farm contributions to catchment in terms of sediment flows. Use of simplified *SedNet* model (constructs sediment and nutrient budgets for regional scale river networks).
5. Scale (catchment vs. farm).
6. Management of vegetation in conservation works; how does this change effectiveness.
7. Changes in effectiveness over time (and spatially).

Scientists: Grant Douglas (AgResearch), John Dymond (Landcare Research), Ian McIvor (HortResearch).

Appendix 2: Regional council staff who provided comments

Stan Braaksma	Greater Wellington Regional Council, Masterton
Dave Cameron	Greater Wellington Regional Council, Masterton
Garth Eyles	Hawke's Bay Regional Council, Napier
Peter Manson	Hawke's Bay Regional Council, Wairoa
John Phillips	Hawke's Bay Regional Council, Napier
Kevin Rooke	Horizons Regional Council, Marton
Don Shearman	Taranaki Regional Council, Stratford
Malcolm Todd	Horizons Regional Council, Palmerston North

Appendix 3: Paper submitted to Environmental Modelling and Software (2007).

An erosion model for evaluating regional land-use scenarios in New Zealand

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Abstract

In New Zealand, the conversion of indigenous forest on hill country to pasture has led to increased mass-movement erosion and sedimentation of waterways. Soil conservation needs to be guided by a model that can evaluate the erosion/sedimentation regime of land use scenarios. In this paper, we develop a model of mean sediment discharge, which is related to mean erosion rates through a sediment delivery ratio. Mean erosion rates within a particular terrain type (termed erosion terrains) are proportional to the square of mean annual rainfall times a cover factor. Measurements of mean sediment discharge are used to calibrate the model within each erosion terrain through an erosion coefficient. The utility of the model is demonstrated on three different applications: evaluation of land use scenarios in the Motueka catchment; prioritisation of soil conservation in the Manawatu catchment; and determination of national trends of agricultural erosion over a 30 year period.

Introduction

Much of the original indigenous forest in New Zealand has been converted to pastoral agriculture. On hill country, where tree roots are an important agent for stabilising soil, deforestation has led to increased soil erosion and consequently increased sedimentation in waterways. This can have detrimental effects on aquatic ecosystems by smothering fish habitat and significantly reducing the penetration of photosynthetically active light. In major catchments where floodbanks have been constructed to reduce the risk of flooding, deposition of sediment in floodways reduces flood conductance. Increased storminess associated with climate change can only exacerbate these negative effects. To mitigate sedimentation in waterways, catchment-wide approaches to reducing soil erosion are required. And for large rivers, this is tantamount to regional approaches to soil conservation. The implementation of farm plans and retirement of steep hill country over large areas is expensive, and needs to be guided by predictive models which link erosion/sedimentation and land use.

Erosion in New Zealand in the long term is dominated by mass movement processes, especially landslides, gullies, and earthflows (Eyles 1983). Modelling of these processes in New Zealand has been confined to a limited number of study areas (Dymond *et al.*, 1999; Meuller, 1998; Claessens *et al.*, 2005; Ekanayake and Phillips, 1999; Hovius *et al.*, 1997; Crozier, 1996). For national and region-wide modelling, Griffiths and Glasby (1985) used an empirical approach to relate measurements of mean sediment discharge at 80 river sites around New Zealand to annual rainfall. They found that mean sediment discharge was proportional to annual rainfall to the power of 2.4. Hicks *et al.* (1996) used 203 sites to determine that mean sediment discharge was a function of rock type and mean annual rainfall (to the power of 1.7). The difficulty with using either the Griffiths and Glasby (1985) or the Hicks *et al.* (1996) model, is that neither involves land

cover as a factor and yet we know from other studies that there is a significant dependence on land cover (Dymond *et al.*, 2006; Page and Trustrum, 1999).

What is required is a model of mean erosion rates that has land cover and land management factors in it, so that proposed land use scenarios can be evaluated in advance. Many different scenarios can be evaluated to make sure that region-wide plans for soil conservation are efficient. In this paper, we formalise the relationship between mean erosion rates and mean sediment discharge through the use of a sediment delivery ratio. This formalisation permits the application of a-priori knowledge of land cover factors of hillslope erosion into an erosion model for use at national and region-wide scales. The model requires stratification of the New Zealand landscape into erosion terrains where erosion processes can be regarded as homogeneous. The utility of the model is demonstrated on three different applications of current interest: evaluation of sediment discharge into the Tasman Bay associated with different land use scenarios in the Motueka catchment; determination of national trends of erosion associated with agriculture over a 30 year period; and prioritisation of soil conservation work in the Manawatu catchment.

Erosion Terrains

Erosion processes are variable throughout NZ, depending on rock type, landform (especially slope angle), and rainfall. We have partitioned New Zealand at the scale of 1:50,000 on the basis of these factors to produce areas with similar erosion processes, called erosion terrains. An erosion terrain is a landscape unit with a unique combination of landform, soils, climate and erosion processes. While differences in land use/management and vegetation cover are important considerations, these were omitted from the definition in order to represent the intrinsic erosion responses independent of factors that can change with time.

A three level hierarchical classification has been used for both the North and South Islands (Appendices 3.1 and 3.2). For the North Island, there are nine groups at the top level differentiated on the basis of landform and slope. At the second level there are 26 groups differentiated on rock type. At the third level there are fifty-two groups differentiated on the basis of erosion processes and further detail of rock type. For the South Island, there are nine groups at the top level differentiated on the basis of landform and slope. At the second level there are 18 groups differentiated on rock type, induration, and presence of loess. At the third level there are 37 groups differentiated on the basis of erosion processes and further detail of rock type.

Model Equations

The model describes long-term mean erosion rates at the source and resulting long-term mean sediment discharge in rivers. The erosion rate at a geographic point (x,y) is defined as the rate of change, with respect to time, of soil depth (m) lost. Erosion rates vary in space and time, so may be denoted by $e(x,y,t)$. The long-term mean erosion rate is denoted by $\bar{e}(x,y)$, and defined by

$$\bar{e}(x,y) = \int^{+T} e(x,y,t)dxdy \qquad (1)$$

where T is of the order of decades.

Similarly the sediment discharge at a point (x,y) in a river is defined as the rate of change, with respect to time, of the volume (m^3) of sediment passing the point.

Sediment discharge varies in space and time, so may be denoted by $s(x,y,t)$. The long-term mean sediment discharge is denoted by $\bar{s}(x,y)$, and defined by

$$\bar{s}(x,y) = \int^{+T} s(x,y,t)\,dx\,dy \qquad (2)$$

The relationship between long-term mean sediment discharge and erosion rate is simple if all the sediment mobilised by erosion reaches a stream where fluvial forces will transport the sediment through the river network. In this case, the sediment discharge is the integral of erosion rate over the watershed above the discharge point. However, sometimes landscapes are disconnected from streams, or erosion processes only deliver a proportion of eroded sediment to streams, and a sediment delivery ratio needs to be considered. The sediment delivery ratio is defined as the ratio of sediment volume delivered to the nearest stream over the volume of eroded soil, and denoted by $D(x,y,t)$. The long-term mean sediment delivery ratio is denoted by $\overline{D}(x,y)$, and defined by

$$\overline{D}(x,y) = \int^{-T} D(x,y,t)\,dx\,dy \qquad (3)$$

The relationship between long-term mean sediment discharge and erosion rate may now be expressed as

$$\bar{s}(x_0,y_0) = \iint_{\substack{catchment \\ above\ (x_0,y_0)}} \overline{D}(x,y)\,\bar{e}(x,y)\,dx\,dy \qquad (4)$$

Hicks *et al.* (1996) and Griffiths (1985) showed that for medium to large catchments, in New Zealand, geology and annual rainfall were important factors for explaining long-term mean sediment discharge. Although land cover was not found to be an important explanatory factor, we know through other studies that it is (Crozier, 1996; De Rose, 1996; Dymond *et al.*, 2006; Dymond *et al.*, 1999; Fransen, 1996; Griffiths and Glasby, 1985; Hicks, 1991; Marden and Rowan, 1993; Pain, 1969; Pain and Stephens, 1990) - it could be there was not sufficient data to investigate the full interaction of geology, rainfall, and land cover. Therefore it is postulated that mean erosion rates are controlled by three factors: erosion terrain; annual rainfall; and land cover.

$$\bar{e}(x,y) = a(x,y)\,C(x,y)\,R(x,y) \qquad (5)$$

where $a(x,y)$ is a constant depending on the erosion terrain (termed the *erosion coefficient*); $R(x,y)$ is the rainfall factor; and $C(x,y)$ is the erosion rate of the land cover at (x,y) relative to forest.

If $C(x,y)$, $R(x,y)$, and $\overline{D}(x,y)$ are all known, then a may be determined for each erosion terrain by applying Equations (4) and (5)

$$a_i = \frac{\bar{s}_i}{\iint_{\substack{erosion \\ terrain\ i}} \overline{D}(x,y)\,C(x,y)\,R(x,y)\,dx\,dy} \qquad (6)$$

where a_i is $a(x,y)$ in the i-th erosion terrain, and $\bar{s}_i$ is the mean annual sediment yield from the i-th erosion terrain.

Model calibration

To determine the erosion coefficients of the model, a_i, for each erosion terrain, the cover factor, $C(x,y)$, the sediment delivery ratio, $\overline{D}(x,y)$, the rainfall factor, P^n, and the mean annual sediment yield for each erosion terrain, $\bar{s}_i$, in equation (6) must be defined.

Cover factor

The cover factor, $C(x,y)$, is the long-term mean erosion rate of the land cover at (x,y) relative to forest at the same point. In tectonically active New Zealand, erosion rates are dominated by mass movement erosion. Studies in North Island hill country have shown that when forest is converted to pasture, long-term erosion rates increase by approximately an order of magnitude (Page and Trustrum, 1999), and so does the magnitude of landsliding events (Dymond *et al.*, 2006). We assume that $C(x,y)$ is dependent on three land covers: woody vegetation, herbaceous vegetation, and bare ground.

$C(x,y)$ = 1 if land cover is woody vegetation

= 10 if land cover is herbaceous vegetation (7)

= 10 if land cover is bare ground

Although we assign pasture and bare ground the same cover factor, we do differentiate between these land covers in case we wish to separate out surficial erosion from mass movement erosion at a later date. A national map of basic land cover at 1:50,000 scale (i.e. 15m pixels) was produced from ETM+ satellite imagery using the method of Dymond *et al.* (2004). Imagery dates varied between the summers of 1999 and 2003.

Sediment delivery ratio

For a national scale model calibration, we do not have enough knowledge to define $\overline{D}(x,y)$ everywhere. Hence we assume that there is no spatial variation in the sediment delivery ratio and is one everywhere. When using the model in areas where the sediment delivery ratio is understood, a digital terrain model may be used to determine whether hillsides are connected to streams or not. In the example of the Manawatu catchment later in the paper, where erosion processes are dominated by landsliding and gullying, we assign

$\overline{D}(x,y)$ = 1 if (x,y) is connected to stream network (8)

= 0 if (x,y) is disconnected from stream network

Connectivity to a stream network is determined with the use of a 15m grid digital elevation model (DEM). A pixel in the DEM is connected if it is possible to traverse down the flow line from the pixel to the nearest stream without encountering a sediment deposition zone, defined as 30m or more of contiguous low slope (below 4 degrees).

Rainfall factor

Griffiths and Gladsby (1986) used a national dataset of mean sediment discharge of 80 rivers to determine a rainfall factor of $P^{2.3}$. Hicks *et al.* (1996) used a revised dataset to determine a rainfall factor of $P^{1.7}$. We evaluated both $P^{1.7}$ and P^{2} and found little difference for the accuracy of the erosion model predictions when compared with measured sediment discharge at the 80 sites. So for the sake of simplicity we assign

$$R(x,y) = P^{2} \qquad (9)$$

A national map of mean annual precipitation on a 100m grid was provided by the Land Environment data layers (Leathwick et al., 2003).

Mean annual sediment yield for each erosion terrain

A national specific sediment yield calculator was produced by NIWA and Landcare as part of a FRST funded project for studying carbon transfers associated with erosion (Hicks et al., in prep). This specific sediment yield calculator was similar to the model here except there was no cover factor, no sediment delivery ratio, and the rainfall factor had an index of 1.7. Measurements of mean sediment discharge at 200 sites were used to calibrate the coefficients for each erosion terrain at the second subgroup level. At the third subgroup level, different methods were adopted, ranging from regression fitting where there was sufficient data, through to defaulting to the second level subgroup value where there was insufficient data. Predicted sediment discharge was then compared with the 200 measurements and systematic bias was removed by introducing correction factors. This was performed twice. For this paper, we summed the specific sediment yield predictions from the calculator over each erosion terrain to produce $\bar{s}_t$.

Results

The erosion coefficients determined from the model calibration are shown in Appendices A and B. The model was then run on the national datasets of rainfall, erosion terrains, and land cover, to produce a national 1:50,000 scale (i.e. 15m pixel) map of long-term mean erosion rates. Figure 1 shows the North Island only. The accuracy of the model was determined by comparing predictions of specific sediment discharge (assuming a sediment delivery ratio of 1 everywhere as in the calibration) with measurements at the 80 sites used by Griffiths (1981) and Griffiths(1982): specific sediment discharge is the sediment discharge divided by catchment area. The log-log plot, shown in Figure 2, has an R^2 of 0.65 and a residual standard error of 0.75.

Examples of use

Motueka catchment land use scenarios

The Motueka river drains an area of 2180 km2 in the Tasman district of the South Island, New Zealand. It flows into the Tasman Bay, which is a productive coastal water body of high economic, ecological, and cultural significance. The estuarine and coastal area around the river mouth is important for a range of commercial fish and shellfish, including scallops, oysters, mussels, cockles, and snapper. The Motueka river contributes about 60% of the total freshwater inflow to the Tasman Bay, carrying with it nutrients and organic matter (Basher, 2003). During floods, high sediment loads restrict recruitment and growth of shellfish. Land use in the Motueka catchment is dominated by indigenous forest, production forestry, and pastoral grazing. Pastoral grazing (especially dairy) is presently achieving greater economic returns than production forestry, so there is pressure to convert from forestry to pastoral agriculture. We use the erosion model to

predict the mean sediment discharge to the Tasman Bay under three different land use scenarios to determine whether changing land use might have detrimental impacts on the ecology of the Tasman Bay.

The three land use scenarios are:

(1) Pre-human vegetation (i.e. indigenous forest everywhere);
(2) Present land use; and
(3) Intensive land use (i.e. conversion of all production forestry in present land use to pastoral agriculture).

To drive the erosion model, a map of basic land cover with three classes (woody vegetation, herbaceous vegetation, and bare ground) is required for each scenario. The land cover map for scenario (2) was created by clipping out the Motueka catchment from the 1:50,000 national map mentioned previously. The land cover maps for scenarios (1) and (3) were created from scenario (2) by recoding the classes. These land cover maps were used to produce cover factor maps, $C(x,y)$, for each scenario. There is little information on sediment delivery ratios in the Motueka catchment, so we assume it is one everywhere. We applied the model to produce maps of mean erosion rates for each scenario and then applied equation (4) to predict the mean sediment discharge into Tasman Bay for each scenario (Table 1). The model shows that the mean sediment discharge of the present land use scenario is double that of the pre-human vegetation, while for the intensive land use scenario it is double again. The environmental impact of these sediment discharges on aquaculture has yet to be determined.

Table 1.

Land use scenario	**Predicted mean sediment discharge** (t/yr)
(1) Pre-human vegetation (indigenous forest everywhere)	150,000
(2) Present land use	320,000
(3) Intensive land use (no production forestry)	750,000

National trends of erosion from agriculture

Ecological economists are desirous of developing an indicator of genuine progress (GPI) in contrast to the gross domestic product (GDP) which indicates economic progress only. As part of the GPI, it is desirous to estimate the total erosion associated with agriculture. The erosion model presented in this paper can be used for this purpose as a simple GIS exercise, as follows. A national land use map (the LCB2) was used to define agricultural land at the date of 2002. The map of agricultural land was overlaid with the national map of mean erosion rates (Figure 2) to determine the mean erosion rate from agricultural land. The mean erosion rate from agricultural land was multiplied by the area of agricultural land to estimate the annual sediment yield from agricultural land in 2002 as 80 million tonnes. If we assume the mean erosion rate from agricultural land is constant in time, then we multiply by the total area of agricultural land, as reported regularly by the Department of Statistics, to obtain a time sequence of annual sediment yields from agriculture (as shown in Figure 3).

Figure 3 here

Prioritisation of soil conservation in the Manawatu catchment

The hill country of the Manawatu-Wanganui region in the North Island has been cleared of indigenous forest for pastoral agriculture. Consequently erosion has accelerated, leaving evidence of slope failure and aggraded river beds. On the 15-16 February 2004 a rainstorm (varying between 150 and 200mm) hit the region causing 62,000 landslides over an area of c. 10,000 km^2. The cost of damage from landsliding, flooding, and siltation was 170 million (NZ) dollars (Trafford, 2004). To mitigate the damage of future events, the regional council is planning to identify erodible land and to encourage the implementation of farm plans, which are designed to increase both productivity and soil conservation. Soil conservation typically involves space-planting of poplars on slopes susceptible to landsliding, planting of poplars to control gully erosion, and willow planting on stream banks to control bank erosion.

We use the erosion model to assess the effectiveness of implementing farm plans in the Manawatu catchment. A realistic scenario of 500 farm plans, at an approximate cost of ten million dollars, was assessed. We assumed that a well implemented farm plan would reduce the long-term average erosion by 70% (Hawley and Dymond reported 80% for landsliding; Hicks (1995) reported 50-80% for landsliding and 30-80% for gullying). In the Manawatu catchment, mean erosion rates are dominated by hillslope processes which can be connected or not to the stream network. Hence we used a 15m pixel DEM to produce a map of the sediment delivery ratio defined in the section "sediment delivery ratio". The erosion coefficients for erosion terrains in the Manawatu were then recalculated using equations (6) and (7). For each farm we calculated the annual sediment yield for the present management and for a fully implemented farm plan (by applying a farm plan factor of 0.3 on pastoral areas). The 500 farms with the largest differences of annual sediment yield between the present management and implemented farm plan were chosen for the scenario. Table 2 compares predictions of mean sediment discharge for subcatchments in the Manawatu, under farm plans, with present discharges. The mean sediment discharge of the Manawatu river reduces from x to y million tonnes per year if the 500 farm plans were fully implemented.

Discussion

Figure 2 shows that the erosion model is able to make predictions of log of mean sediment discharge with an uncertainty of plus or minus 0.75 at 68% confidence. However, not all of this variation can be ascribed to the uncertainty of the model, as some will be due to errors in measuring mean sediment yield (sediment rating curves often have large uncertainty). The influence of model uncertainty depends on model use. In the national example, the total amount of agricultural sediment yield (95 million tonnes in the mid 1980s) and the relative trend are important. The total amount will have little uncertainty as it is the summation of many independent estimates. However, the range of the trend line is strongly dependent on cover factor, as in the Motueka example, so the uncertainty of the range is primarily controlled by the uncertainty of the cover factor, which is large. In the Manawatu example, of interest is how many farm plans (and the associated cost) need to be implemented to achieve a target reduction in mean sediment discharge, and the priority order of farms. The uncertainty of the number of farms is primarily controlled by the uncertainty of the farm plan factor, which is large. The priority order of farms is more controlled by the uncertainty of the erosion coefficients associated with each erosion terrain, and these have moderate uncertainty.

The erosion model relates long-term mean sediment discharge with erosion rates through a sediment delivery ratio. The sediment delivery ratio is not always well known. It requires an understanding of the dominating erosion processes, which can of course vary in time. If landslides are dominating, then the sediment delivery ratio will tend to be midway between 0 and 1 as landslides usually leave material behind on the slopes as

they travel down to the nearest stream (Crozier, 1996; Page, 1999). If gully erosion is dominating then the sediment delivery ratio will be close to 1, as the gullies by definition are connected directly with the stream network. In the example applications where sediment delivery ratios are not well known, we have recommended that a sediment delivery ratio of 1 everywhere be adopted. For very long periods of time (~ thousands of years), we would expect this to be the case, as most eroded sediment travels through a catchment system eventually. Over periods of decades, this is not necessarily the case, and the assumption of unity everywhere, will distort the predicted spatial pattern of erosion rates. However, the predicted sediment discharge will not be affected as much. Where the spatial pattern of erosion is important, as it is for individual farm plans, then dominating erosion processes would have to be assessed to better estimate the sediment delivery ratio. In future, we intend to investigate the possibility of using more physically-based models of erosion processes to estimate sediment delivery ratios.

The erosion model bears similarities with the USLE model of surficial soil erosion: there are rainfall and cover factors; and the erosion coefficients act like the soil erodibility factor. The main point of difference is that our erosion model excludes an explicit slope factor. However, the erosion terrains are differentiated at the top level on the basis of slope and topography, and so a slope factor is implicit in the erosion coefficients shown in Appendices 3.1 and 3.2. Indeed the general trend of increasing erosion coefficient with the label number is due to increasing slope angle. This implicit handling of slope angle means that there will be no differentiation of erosion rates within a particular hillside where slopes may vary from steep through to flat. Theoretically it is possible to introduce an explicit slope factor and to further modify the erosion coefficients as for the cover factor, but we prefer to consider the hillside rather than the hillslope component as the minimum object for the model.

The erosion model is a useful construct for estimating mean erosion rates and sediment discharge under land use scenarios where there is a comprehensive network of sediment discharge data. Measured sediment discharge is essentially spread around the landscape through an empirical relationship involving GIS layers of mean annual rainfall, land use, and erosion terrains. The inclusion of the land use layer permits the evaluation of land use scenarios. The model can be applied rapidly and simply over large areas, such as large catchments, districts, or regions. The modelling approach can be used elsewhere in the world where there is a good network of sediment discharge data and GIS layers of biophysical data. As such, the approach provides a useful alternative to the application of physically-based models (e.g. Ewen *et al.*, 2000; Beasley *et al.*, 1980; Doten *et al.*, 2006), which are presently limited to catchment-wide applications because of the requirement for many input parameters and intensive computation.

Conclusions

Over a diverse range of landscapes, in New Zealand, long-term erosion rates are dominated by terrain type, mean annual rainfall squared, and vegetation cover. Sediment discharge measurements can be used to calibrate the relationship and derive an erosion coefficient for each erosion terrain type. This erosion model can be combined with a sediment delivery ratio to produce predictions of mean sediment discharge in response to land cover/ land use scenarios. The model is easy to execute and uses input data readily available in GIS layers in New Zealand, thus providing a useful alternative to physically-based models.

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Appendix 3.1. North Island erosion terrains

Label	Description	Erosion coefficient (by 10^5) *
	Active flood plains	
1.1.1	undifferentiated alluvium from modern overbank depositional events. parts may be peaty. includes non-peaty wetlands	
	Sand country	
2.1.1	recent fresh dune sand	
2.1.2	mature moderately weathered dune sand	
	Peatland	
3.1.1	organic soils on deep peat	
	Terraces, low fans, laharic aprons (most slopes <8o)	
4.1.1	loess	
4.1.2	young tephra, mostly pumiceous (waimihia and younger)	
4.1.3	basins infilled with Taupe tephra flow deposits—intensely gullied	
4.1.4	mid-aged (late pleistocene/early holocene) tephra, older tephra, or tephric loess	
4.2.1	fine grained, weathered, undifferentiated terrace alluvium—above the level of modern flood plains	
4.3.1	gravelly soils on alluvial terrace gravels or on gravelly laharic aprons—above the level of modern flood plains	
	Downland (most slopes 8–15o)	
5.1.1	loess	
5.1.2	young tephra (waimihia and younger), over older tephra	
5.1.3	mid-aged (late pleistocene/early holocene) tephra, older tephra, or tephric loess	
5.2.1	young basalt lava fields and low domes (parts are flatter than typical downland)	
5.3.1	weathered sedimentary and non-tephric igneous rocks	
	Hill country (most slopes 16–25o)	
6.1.1	loess	
6.1.2	young tephra (waimihia or younger), usually over older tephra—shallow (0.3–1.0 m)	
6.1.3	young tephra (waimihia or younger), usually over older tephra—deep (>1.0 m)	
6.1.4	mid-aged (late pleistocene/early holocene) tephra, or tephric loess	
6.2.1	relatively young basalt domes and cones	
6.3.1	weak to very weak tertiary-aged mudstone	
6.3.2	crushed tertiary-aged mudstone, sandstone; argillite, or ancient volcanic rock (frequently, with tephra covers in the northern Hawke's bay–east coast area) —with moderate earthflow-dominated erosion	
6.3.3	crushed mudstone or argillite with severe earthflow-dominated erosion	
6.3.4	crushed argillite, sandstone, or greywacke, with severe gully-dominated erosion	
6.4.1	cohesive, generally weak to moderately strong tertiary-aged sandstone	
6.4.2	non-cohesive tertiary-aged sandstone	
6.5.1	limestone	
6.6.1	unweathered to moderately weathered greywacke/argillite	
6.6.2	unweathered to slightly weathered white argillite	

6.7.1	residual weathered to highly (often deeply) weathered tertiary-aged sedimentary rocks	
6.7.2	residual weathered to highly (often deeply) weathered ancient basalt and andesite	
6.7.3	residual weathered to highly (often deeply) weathered welded rhyolite	
6.7.4	residual weathered to highly (often deeply) weathered greywacke/argillite	
	Hilly steeplands (most slopes >25o)	
7.1.1	young tephra (waimihia or younger), usually over older tephra—shallow (0.3–1.0 m) covers	
7.1.2	young tephra (waimihia or younger), usually over older tephra—deep (>1.0 m)	
7.1.3	mid-aged (late pleistocene/early holocene) tephra	
7.2.1	fresh to slightly weathered welded rhyolitic rock, or bouldery andesitic lahar deposits	
7.3.1	weak to very weak tertiary-aged mudstone	
7.3.2	crushed argillite with gully-dominated erosion	
7.4.1	cohesive, generally weak to moderately strong tertiary-aged sandstone	
7.4.2	non-cohesive tertiary-aged sandstone, and younger sandy gravels and gravelly sands	
7.5.1	limestone	
7.6.1	unweathered to moderately weathered greywacke/argillite	
7.6.2	unweathered to slightly weathered white argillite	
7.7.1	residual weathered to highly (often deeply) weathered ancient basalt and andesite	
7.7.2	residual weathered to highly (often deeply) weathered welded rhyolite	
7.7.3	residual weathered to highly (often deeply) weathered greywacke/argillite	
	Upland plains and plateaux	
8.1.1	upland plains and plateaux with tephra covers	
	Mountain steeplands	
9.1.1	greywacke/argillite or younger sedimentary rocks of the main ranges prone to landslide erosion	
9.1.2	greywacke/argillite or younger sedimentary rocks of the main ranges prone to sheet/wind/scree erosion	
9.2.1	volcanic rocks in mountain terrains and upland hills	
9.2.2	upper flanks of volcanoes	

* not presented; data pending external review for journal publication.

Appendix 3.2. South Island erosion terrains

Label	Description	Erosion coefficient (by 10^6) *
	Active flood plains	
1.1.1	recent (young), active floodplains and fans flat to gently sloping.	
	Sand country	
2.1.1	coastal sand dunes, beach ridges, flat to moderately sloping sand flats, sand dunes	
	Peatland	
3.1.1	peat deposits flat to gently undulating peat swamps, domed and upland peat deposits	
	Terraces and fans	
4.1.1	flat to gently sloping terraces and fans of older alluvium above the floodplain	
4.2.1	loess on flat to gently sloping terraces and fans of older alluvium above recent floodplain	
	Downland (most slopes 4-15 degrees)	
5.1.1	moraine and dissected alluvium	
5.2.1	loess > 1m deep	
5.3.1	soft sedimentary rocks	
5.4.1	hard sedimentary rocks	
5.4.2	hard schist rocks	
5.4.3	hard coarse grained igneous or metamorphic and fine igneous rocks	
	Hill country (most slopes 16-25 degrees)	
6.1.1	moraine or dissected alluvium	
6.2.1	loess > 1m deep	
6.3.1	soft sedimentary mudstone	
6.3.2	soft sedimentary sandstone	
6.3.3	soft sedimentary conglomerate	
6.3.4	soft calcareous sediments	
6.4.1	hard sedimentary rocks	
6.4.2	hard schist rocks	
6.4.3	hard coarse grained igneous or metamorphic rocks	
6.4.4	hard fine grained igneous rocks	
	Hilly steeplands (most slopes > 25 degrees)	
7.1.1	soft mudstone	
7.1.2	soft sandstone	
7.1.3	Soft conglomerate	
7.2.1	hard sedimentary rocks	
7.2.2	hard schist rocks	
7.2.3	hard coarse grained igneous or meatmorphic rocks	
7.2.4	hard carbonate rocks	
7.2.5	fine grained igneous rocks	
7.3.1	weathered hard schist & greywacke rocks	
7.3.2	weathered coarse grained igneous rocks	

	Mountain steeplands	
8.1.1	hard sedimentary rocks	
8.1.2	hard schist rocks	
8.1.3	hard coarse grained igneous and metamorphic rocks	
8.1.4	hard fine grained igneous	
8.1.5	weathered coarse grained igneous rocks	
9	alpine slopes - very steep to precipitous mountain slopes	

* not presented; data pending external review for journal publication.

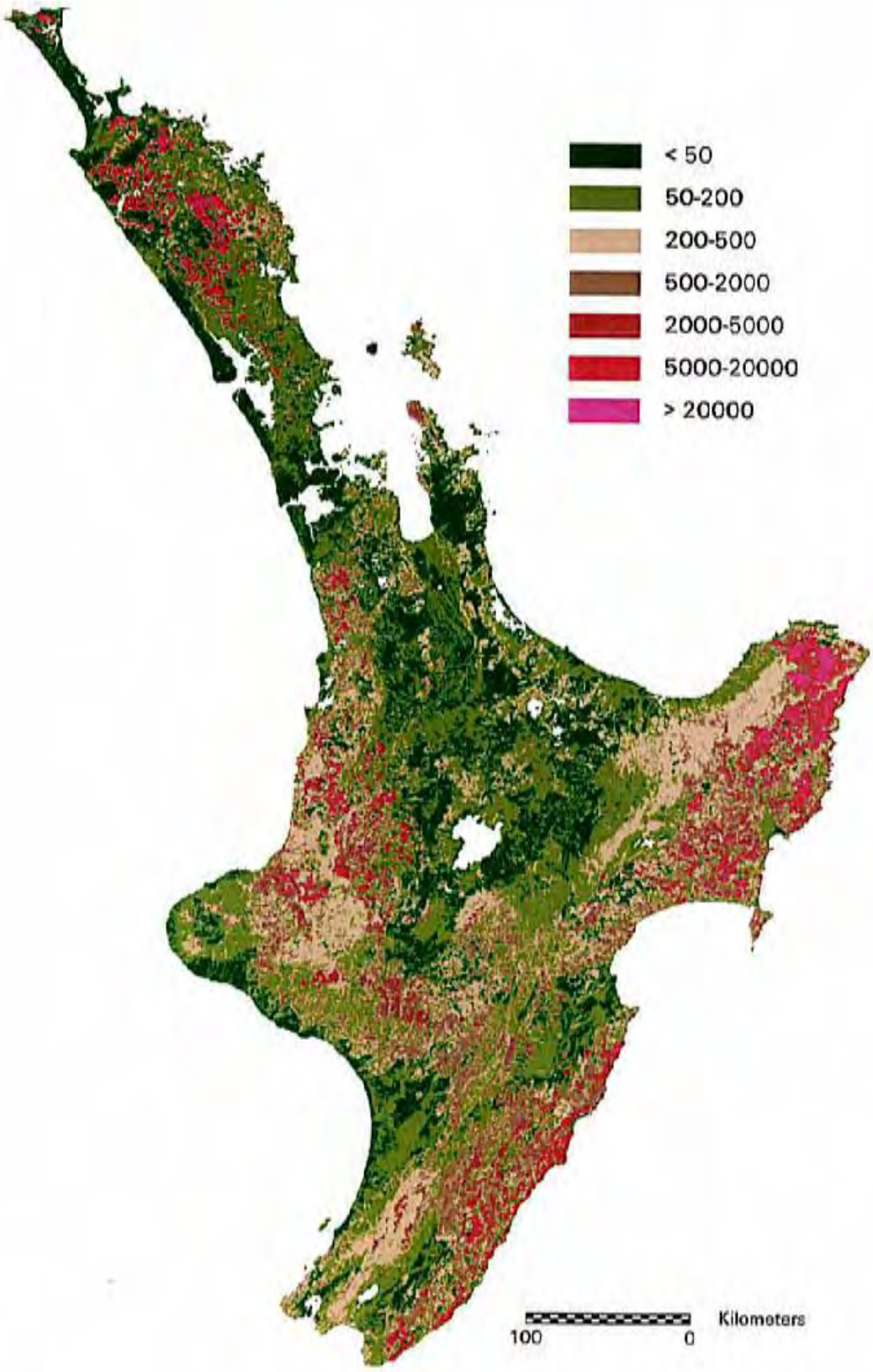

Figure 1: Predicted mean erosion rates for the North Island of New Zealand under current land cover. Units are tonnes.km^{-2}.yr^{-1}.

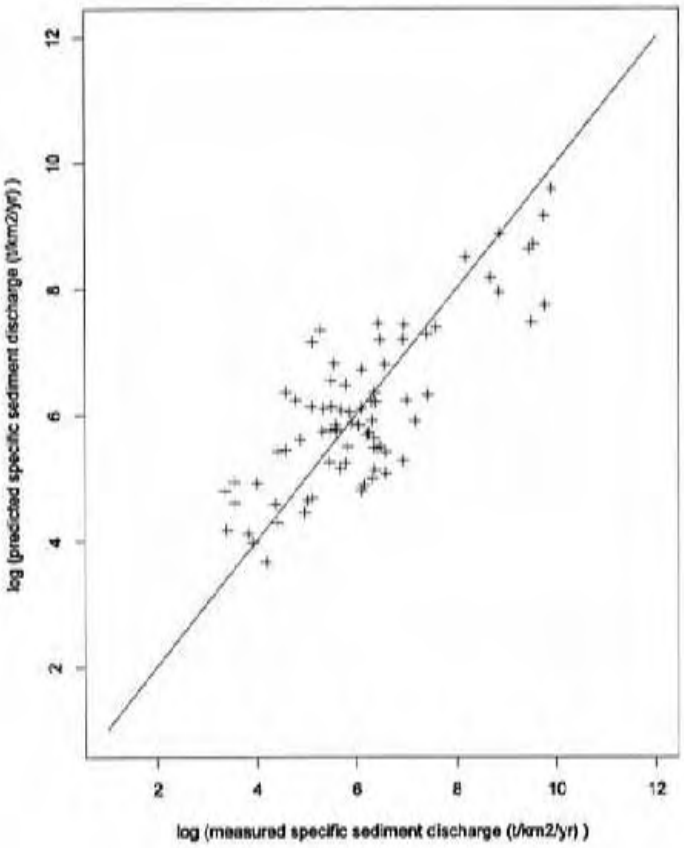

Figure 2: Log-log plot of predicted versus measured specific sediment discharge for 80 sites spread throughout New Zealand. R^2 is 0.65

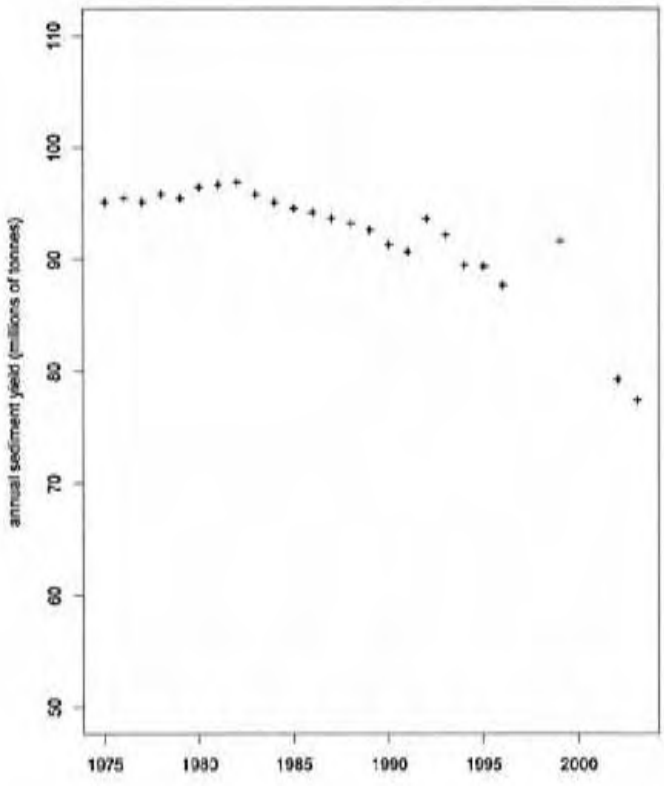

Figure 3: Total annual sediment yields from agriculture in New Zealand over the past 30 years.