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Soil erosion in New Zealand is a net sink of CO_2

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Earth Surface Processes and Landforms

ABSTRACT: Soil erosion in New Zealand exports much sediment and particulate organic carbon (POC) to the sea. The influence of this carbon export on carbon transfers between soils and the atmosphere has been largely unknown. Erosion models are used to estimate the net carbon transfer between soils and atmosphere due to soil erosion for New Zealand. The models are used to estimate the spatial distribution of erosion, which is combined with a digital map of soil organic carbon content to produce the spatial distribution of carbon erosion. The sequestration of atmospheric CO_2 by regenerating soils is estimated by combining carbon recovery data with the age distribution of soils since erosion occurrence. The North Island of New Zealand is estimated to export 1·9 (with uncertainty of –0·5 and +1·0) million tonnes of POC per year to the sea and to sequester 1·25 (–0·3 /+0·6) million tonnes of carbon per year from the atmosphere through regenerating soils. The South Island of New Zealand is estimated to export 2·9 (–0·7/+1·5) million tonnes of POC per year and to sequester approximately the same amount. Assuming exported carbon is buried at sea with an efficiency of 80% gives New Zealand a net carbon sink of 3·1 (–2·0/+2·5) million tonnes per year; which is equivalent to 45% of New Zealand's fossil fuel carbon emissions in 1990. The net sink primarily results from a conveyor belt transfer of carbon from the atmosphere to soils regenerating from erosion to the sea floor where carbon is permanently buried. The net sink due to soil erosion can be further increased by reforestation of those terrains where erosion is excessive and there is no carbon recovery in the soils.

KEYWORDS: soil carbon; carbon sink; carbon sequestration; soil recovery

Introduction

Carbon dioxide from the burning of fossil fuels enters the atmosphere and, subsequently, the carbon reservoirs of the ocean and terrestrial biosphere. Global budgeting of the known transfers of carbon between these reservoirs has revealed a residual sink (a 'missing sink') of approximately 2000 million tonnes of carbon per year (Schimel, 1995; Denman *et al.*, 2007). Stallard (1998) investigated global scenarios of carbon burial caused by soil erosion and found that a net sink of approximately 1000 million tonnes per year was possible, thereby providing a plausible explanation for a major part of the residual sink. Given the importance of soil erosion in the global carbon cycle and a strong link with human activities through land use, it is beneficial to evaluate more carefully the carbon transfers associated with soil erosion (Kuhn *et al.*, 2009).

There has been disagreement in the scientific literature over the relationship between soil erosion and carbon sequestration. Some studies concluded that soil erosion was a net emitter of carbon dioxide (CO_2) (Lal, 2003; Post *et al.*, 2004); others that soil erosion was a net sink of carbon (Stallard, 1998; Smith *et al.*, 2001; Harden *et al.*, 1999; Yoo *et al.*, 2005; Liu *et al.*, 2003; McCarty and Ritchie, 2002). Contrary to both of these conclusions, Van Oost *et al.* (2007) concluded that soil erosion was neither an important source nor an important sink for CO_2. Berhe *et al.* (2007) suggested criteria for demonstrating an erosion-induced carbon sink, that is, dynamic replacement of eroded carbon and reduced decomposition rates in depositional sites must together more than compensate for erosion losses. They applied this to determine that soil erosion is a net sink of carbon globally (~700 million tonnes per year). Kuhn *et al.* (2009) reopened the debate by asserting that a reconciliation of the two positions is only possible through a more careful consideration of the fate of carbon as it moves through the landscape, especially with inter-rill erosion.

New Zealand is a high-standing island in the southwest Pacific with generally high rainfall and consequently high erosion rates primarily through mass-movement (Eyles, 1983). Lyons *et al.* (2002) estimated that riverine export of particulate organic carbon (POC) to the sea from high-standing islands in the southwest Pacific (Indonesia, Malaysia, Papua New Guinea, Phillipines, Taiwan, and New Zealand) is approximately 50 million tonnes per year (POC is the organic carbon in suspended solid particles). This forms a significant portion of the total global export to the sea of 150 million tonnes. Sequestration of carbon by regenerating soils and the release of erosion-derived CO_2 from the ocean to the atmosphere was not estimated. Tate *et al.* (2000) estimated for New Zealand the loss of soil organic carbon (SOC) to the sea through soil erosion was between three and 11 million tonnes per year. Again, sequestration by regenerating soils and release of erosion-derived CO_2 from the ocean was not estimated. Scott *et al.* (2006) estimated the export of POC from New Zealand rivers to be 2·7 (±1·0) million tonnes per year. Page *et al.*

(2004), examining lake sediments to estimate a more comprehensive erosion carbon budget for a pastoral steepland catchment, concluded that SOC exported through human-induced erosion would be nationally significant, and that the carbon export was offset by sequestration on recovering landslide scars.

In this paper, erosion models are used to estimate the net carbon transfer between the atmosphere and soils due to erosion in New Zealand. The models are used to estimate the spatial distribution of erosion rates, which are then combined with a digital map of SOC content to produce the spatial distribution of carbon erosion. For 89 types of land, called erosion terrains and described in the next section, the sequestration of SOC is estimated by combining soil carbon recovery data with age distribution since erosion occurrence. Assuming a high burial efficiency of erosion carbon at sea, suggested by recent research (Galy *et al.*, 2007), the net transfer of carbon between the atmosphere and soils (due to erosion) is estimated for each erosion terrain. The budgets for each erosion terrain are amalgamated for the North and South Islands separately: the North Island is dominated by human-induced erosion caused by deforestation of hill country (~1900); while the South Island is dominated by natural erosion in the Southern Alps. For the North Island, both present-day erosion-carbon budgets and budgets for before and immediately after deforestation are calculated. The processes to be considered are removal of organic carbon by erosion, redistribution and burial on the landscape, transport to and burial by the sea or release to the atmosphere, and sequestration of atmospheric CO_2 by soils recovering from erosion.

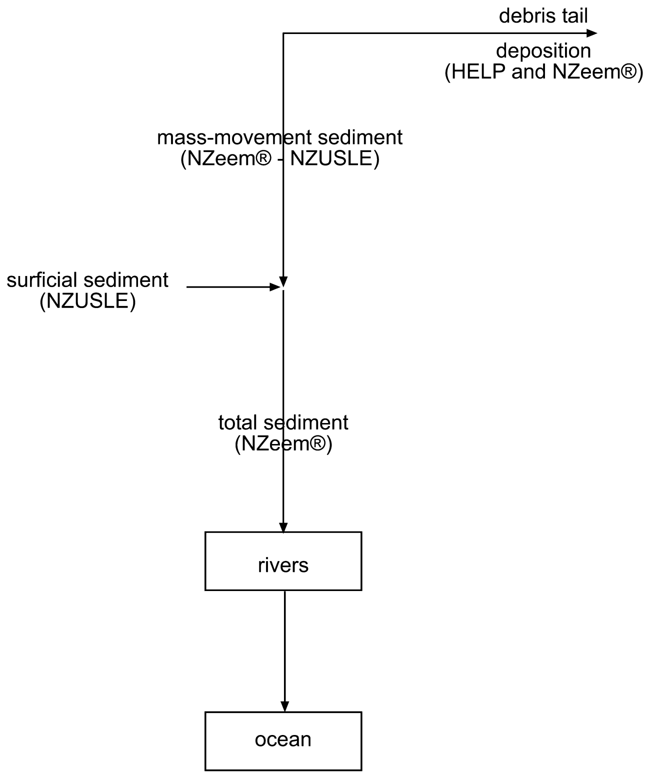

Figure 1. Schematic showing how the erosion models are used to calculate sediment transfers in landslide terrains. In gully and earthflow terrains there is no deposition of sediment through debris tails. Surficial erosion is usually an order of magnitude less than mass-movement erosion for terrains where mass-movement occurs.

Erosion Terrains

Erosion processes vary throughout New Zealand, depending on rock type, landform, slope, and rainfall. New Zealand was partitioned on the basis of these factors at the scale of 1 : 50 000 into areas with similar erosion processes (i.e. erosion terrains) by amalgamating land-use capability units from the New Zealand Land Resource Inventory (Eyles, 1983). While differences in land use or management and vegetation cover are important, these were omitted from the definition in order to represent intrinsic erosion susceptibility independently from factors that can change with time. A three-level hierarchical classification was used for both the North and South Islands. For the North Island, nine groups were differentiated at the top level on the basis of landform and slope. At the second level, 26 groups were differentiated by rock type. At the third level, 52 groups were differentiated on the basis of erosion processes and further detail of rock type. For the South Island, nine groups were differentiated at the top level, based on landform and slope. At the second level, 18 groups were differentiated by rock type, induration, and presence of loess; and at the third level, 37 groups were differentiated on the basis of erosion processes and further detail of rock type. Dymond *et al.* (2010) give a detailed list of the erosion terrains.

Methods

Erosion models and soil organic carbon (SOC) content

The carbon loss from a point due to soil erosion is the product of the erosion rate by the SOC concentration of the soil eroded. The carbon concentration of soil decreases with depth, so it is necessary to know the depth to which the erosion takes place. Two separate models are used for this: the New Zealand empirical erosion model (NZeem®) is used to estimate total erosion from all erosion processes; and a New Zealand Universal Soil Loss Equation (NZUSLE) is used to estimate erosion from surficial erosion processes. Surficial erosion is assumed to involve soil from the top 10 cm, while mass movement erosion is assumed to involve soil from the top 1 m. A third erosion model, the Highly Erodible Land (HEL) model, is used to estimate the sediment delivery ratio for land dominated by landslide erosion, which is required for estimating the annual rate of landslide scar production and deposition of sediment by debris tails. Figure 1 shows a schematic of how the models are used.

Three national raster layers of SOC concentration (0–10 cm, 10–30 cm, and 30–100 cm) were derived from a multiple regression of 1827 measurements of SOC throughout New Zealand on relevant variables existing as national geographic information system (GIS) layers. These variables included soil type, land cover, elevation, slope, latitude, mean annual rainfall, mean water deficit, mean solar radiation, and mean annual minimum temperature. The root mean squared (r.m.s.) errors of mean SOC concentration for erosions terrains were typically 0·04, 0·05, and 0·07, for depths of: 0–10 cm, 10–30 cm, and 30–100 cm.

New Zealand empirical erosion model (NZeem®)
The total erosion rate, $\bar{e}$ (x, y) is estimated from three factors: erosion terrain; mean annual rainfall; and land cover:

$$\bar{e}(x,y) = a(x,y)C(x,y)P^2(x,y) \tag{1}$$

where $\bar{e}$ (x, y) is the mean annual erosion rate (in t km^{-2} yr^{-1}); x is easting; y is northing; $a(x,y)$ is an empirical constant (in t km^{-2} yr^{-1} mm^{-2}) depending on the erosion terrain (termed the erosion coefficient) and is determined by calibration of the model with measurements of long-term sediment yield from 200 sites around New Zealand (Dymond *et al.*, 2010); $P(x,y)$ is the mean annual rainfall (in millimetres); and $C(x,y)$ is the land cover factor given by the erosion rate of the land cover at (x,y) relative to forest.

In tectonically active New Zealand, erosion rates are dominated by mass-movement erosion. Studies in North Island hill country have shown the conversion of forest to pasture increases long-term erosion rates by approximately an order of magnitude (Page and Trustrum, 1997) and also increases erosion rates in major landsliding events (Dymond *et al.*, 2006; Marden and Rowan 1993). Dymond *et al.* (2010) assigned $C(x,y)$ as follows:

$$\begin{aligned} C(x,y) &= 1 \text{ if land cover is woody vegetation} \\ &= 10 \text{ if land cover is herbaceous vegetation} \\ &= 10 \text{ if land cover is bare ground} \end{aligned} \quad (2)$$

They assigned pasture and bare ground the same cover factor as neither have deep and strong roots sufficient for strengthening soil to the depth of bedrock. Even though bare ground has a much higher surficial erosion rate than herbaceous vegetation, it was considered unimportant as surficial erosion is dominated by mass-movement erosion (Eyles, 1983). It could be that herbaceous vegetation has a greater drying effect than bare ground, thus reducing pore-water pressures and the risk of mass-movement erosion. However, there are no data to support this and given there is very little bare ground in New Zealand (particularly in areas where land-use change occurs) assigning the same cover factor to bare ground is not critical.

A national map of cover factor at 1 : 50 000 scale (i.e. 15 m pixels) was produced from ETM+ satellite imagery using the method of Dymond and Shepherd (2004). Imagery dates varied between the summers of 1999/2000 and 2002/2003. Figure 2 shows the spatial distribution of erosion rates in New Zealand estimated using NZeem®. The date is nominally 2001, but with little land-cover change over the last seven years it may be used to estimate rates in 2008 (Shepherd, 2009; Newsome, 2009). Figure 3 compares NZeem® predictions of sediment yield in tonnes per year with measurements at 80 river sites throughout New Zealand (Dymond *et al.*, 2010). The explained proportion of variance in the measured sediment yields is 65%.

New Zealand Universal Soil Loss Equation (NZUSLE)

NZUSLE was developed for estimating erosion rates from surficial erosion processes (i.e. rill and inter-rill erosion). It has the same factors as the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), except that the rainfall factor is a function of mean annual rainfall only (following Mitchell and Bubenzer, 1980). The NZUSLE was calibrated using published data of surficial erosion rates in New Zealand (Soons and Rainer, 1968; Mosley, 1980; O'Loughlin *et al.*, 1978, 1980; O'Loughlin, 1984; Benny and Stephens, 1985; Lambert *et al.*, 1985; Wilcock, 1986; Dons, 1987; Wilcock *et al.*, 1999; Cooper *et al.*, 1992; Fahey and Coker, 1992; Smith, 1992; Smith and Fenton, 1993; Basher *et al.*, 1997; Fahey and Marden, 2000; Rodda *et al.*, 2001; Quinn and Stroud, 2002). NZUSLE gives the mean annual erosion rate caused by surficial erosion processes as a product of five factors

$$\bar{e}_s(x,y) = \alpha P^2(x,y)K(x,y)L(x,y)Z(x,y)U(x,y) \quad (3)$$

where $\bar{e}_s$ (x, y) is the mean annual erosion rate due to surficial processes (in t km^{-2} yr^{-1}); α is a constant calibrated with published surficial erosion rates ($1{\cdot}2 \times 10^{-3}$); $P(x,y)$ is mean annual rainfall (in millimetres); $K(x,y)$ is the soil erodibility factor (sand 0·05; silt 0·35; clay 0·20; loam 0·25); $L(x,y)$ is the slope length factor $(\lambda/22)^{0.5}$ where λ is slope length in metres; $U(x,y)$ is a vegetation cover factor (bare ground 1·0, pasture 0·01, scrub 0·005, forest 0·005); and $Z(x,y) = 0{\cdot}065 + 4{\cdot}56\frac{dz}{dx} + 65{\cdot}41\left(\frac{dz}{dx}\right)^2$ where dz/dx is the slope gradient (no units).

Figure 4 compares NZUSLE predictions with the published measurements. The explained proportion of variance in the measured surficial erosion rate is 60%.

Highly Erodible Land (HEL) model

The HEL model identifies land susceptible to landsliding from three national GIS layers: a land-cover map; a slope map from a digital elevation model (DEM); and an erosion terrain map. The GIS layers are rasters with 15 m pixels. For every pixel, the slope is examined to see if it exceeds a threshold set for each rock type (Dymond *et al.*, 2006; Dymond *et al.*, 2010). If a pixel exceeds the slope threshold and does not have woody vegetation in the land cover map, it is identified as land susceptible to landsliding; in that case, the flow path down to the nearest stream is traversed in the DEM, using flow direction and flow accumulation, to decide whether the pixel can deliver landslide debris to the stream network and ultimately the ocean. If the flow path encounters any significant flat land, that is, two consecutive pixels below four degrees of slope, then the original susceptible pixel is tagged as 'non-contributing', because sediment will deposit on the flat land before it reaches a stream. Erosion in this case simply redistributes carbon within the New Zealand land area but provides no net flux to the ocean. Otherwise, the pixel is tagged as 'contributing'. The proportion of HEL land in an erosion terrain that is tagged as 'contributing' is an approximation of the sediment delivery ratio, that is, the proportion of eroded sediment reaching streams and ultimately the ocean.

National erosion carbon budget

The annual net emission of carbon to the atmosphere from the soil due to erosion processes is denoted by G (in t yr^{-1}). It may be estimated by

$$G = D + f_s O - R \quad (4)$$

where D is the annual net transfer of carbon to the atmosphere associated with deposition of soil on the landscape (in t yr^{-1}) (this includes decomposition of buried soils and regeneration of deposited sediment); O is the annual yield of carbon to the sea (in t yr^{-1}) and f_s is the fraction of that not permanently buried and eventually released to the atmosphere; and R is the annual mass of carbon sequestered from the atmosphere in soils regenerating at erosion sites (in t yr^{-1}).

New Zealand is a high-standing oceanic island delivering a large mass of sediment to the ocean every year (Lyons *et al.*, 2002). The associated organic carbon will therefore most likely be buried efficiently on the ocean floor with the sediment (Galy *et al.*, 2007; Masiello, 2007). Assuming the burial efficiency ranges somewhere between 0·6 and 1·0, a nominal value of 0·2 (±0·2) is assigned to f_s. A national budget of G requires the estimation of D, O and R for each erosion terrain in New Zealand.

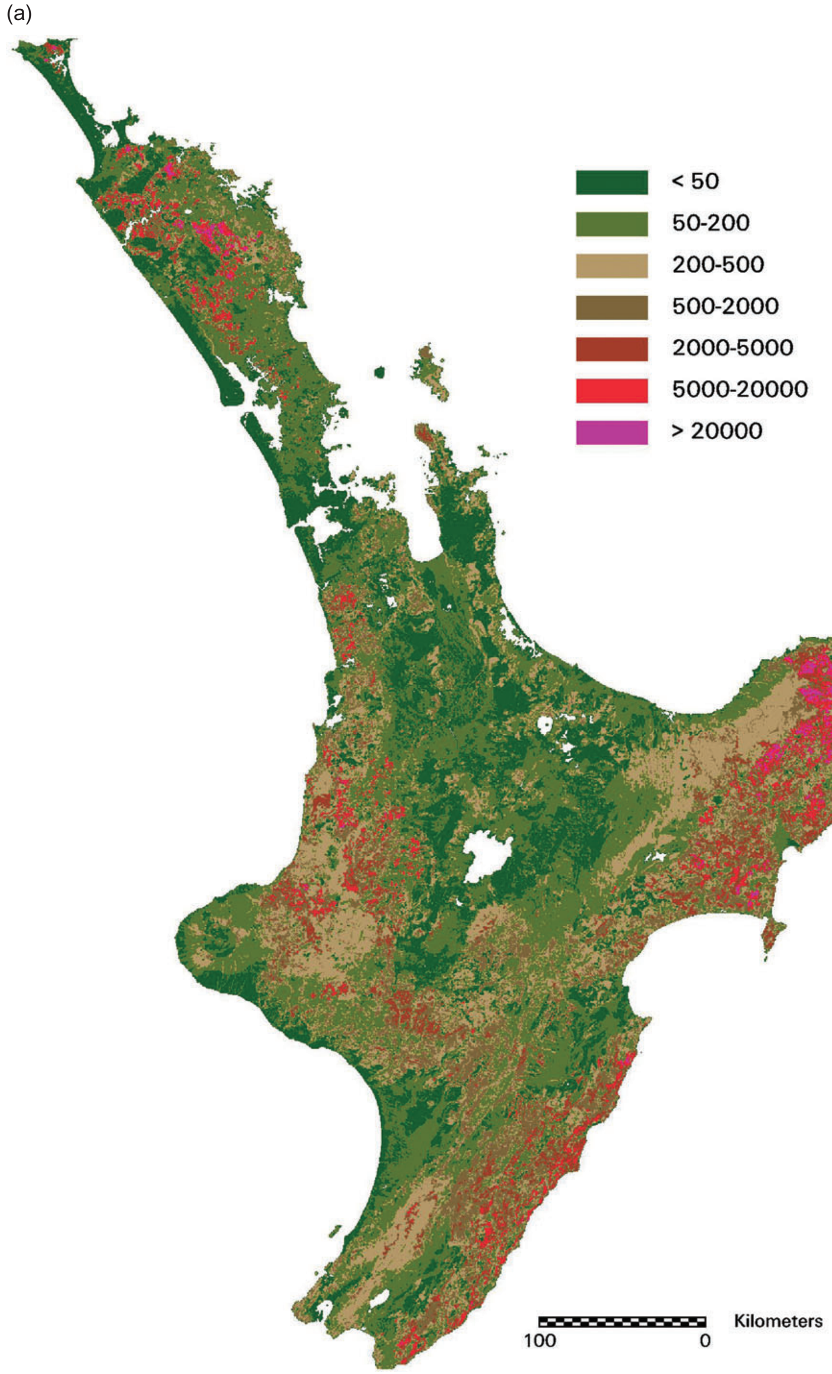

Figure 2. Spatial distribution of erosion rates (in t km^{-2} yr^{-1}) in (a) North Island (year 2001) and (b) in South Island (year 2001) estimated from NZeem®. Source: digital data exist on a 15-m grid.

Carbon yield to the sea

A raster GIS layer (15-m pixels) of total erosion rate was produced for each erosion terrain using NZeem®. The mean value for the erosion terrain is denoted by S and comprises all erosion processes on the landscape. Because the carbon content of soil increases with depth, it is necessary to apportion the total erosion into surficial (shallow) and mass movement (deep). The NZUSLE was used to estimate mean surficial erosion rates for each erosion terrain and thence the proportion of total erosion, denoted by p_s. The annual yield of carbon to the sea, O, from the erosion terrain, may then be estimated by the product of the sediment yield with the mean carbon concentration of that sediment:

$$O = [(1 - p_s)C_{100} + p_s C_{10}]SA \tag{5}$$

where S is the mean annual erosion rate for the erosion terrain (in t km^{-2} yr^{-1}); A is the area of the erosion terrain in kilometres squared; C_{100} is the mean SOC concentration of the top 100 cm of soil for the erosion terrain (no unit); C_{10} is the mean SOC concentration of the top 10 cm of soil for the erosion terrain (no unit).

Carbon sequestration in regenerating soils

In the South Island, erosion is dominated by natural processes in the Southern Alps and there have been no major perturbations of the climate or vegetation in the last 5000 years. Soil erosion and regeneration of soils can therefore be assumed approximately in balance (Stallard, 1998), that is, $O \approx R$; and the net transfer of SOC to the atmosphere associated with deposition of soil can also be assumed approximately zero,

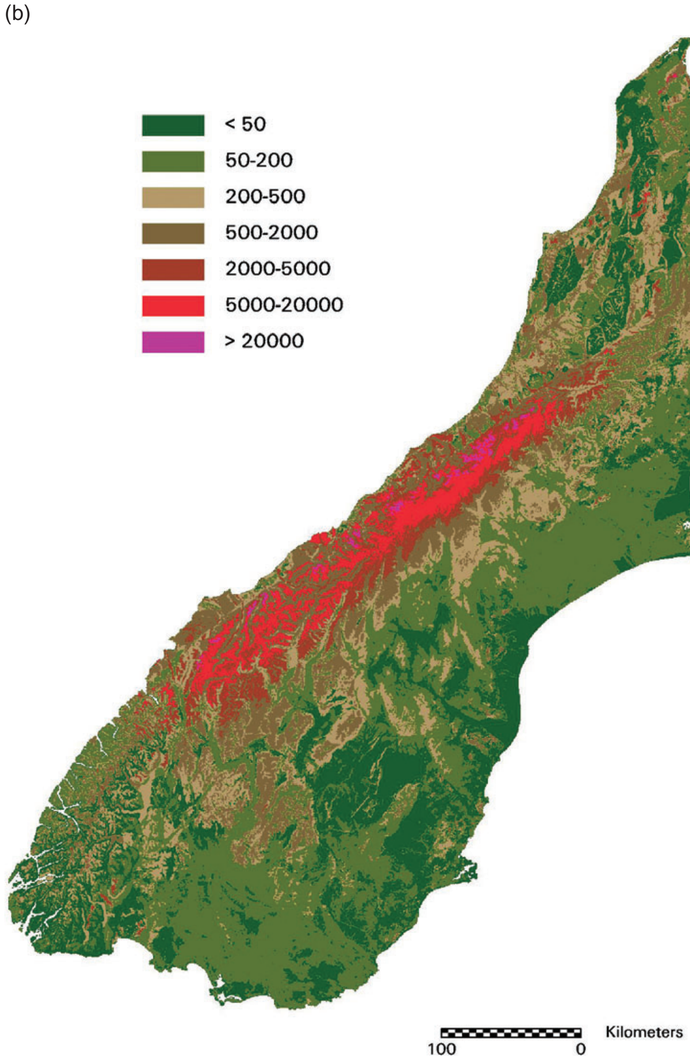

Figure 2. *Continued.*

that is, $D \approx 0$. However, in the North Island, erosion is primarily caused by deforestation in hill country, occurring *c.* 110 years BP. So regeneration of soils is not necessarily in balance with erosion and needs to be estimated independently of R.

There are three processes by which carbon can be sequestered into soils regenerating after erosion:

- shallow landslides remove the soil profile down to bedrock (~100 cm) which regenerates back to a near normal soil with a depth of ~100 cm after about a 100 years (Lambert *et al.*, 1984);
- the debris tails of landslides deposit on hillslides at a depth much shallower than the scar depth and with a carbon content equal to the average of the top 100 cm, and will sequester carbon until the normal carbon content of the top 10 cm is attained;
- surficial erosion occurs everywhere and the carbon lost will be approximately balanced by soil regeneration.

On erosion terrains dominated by gully erosion and earthflow there are assumed to be no landslides and consequently no old landslide scars sequestering carbon. On erosion terrains dominated by landslide erosion the carbon exported from mass-movement erosion is assumed to recover on the old scars at a rate given by an exponential recovery curve (Page *et al.*, 2004):

$$C_s = C_{100}(1 - e^{-0{\cdot}03t}) \qquad (6)$$

where C_s is the SOC concentration of soil on a landslide scar t years after failure, and C_{100} is the mean SOC concentration of the top 100 cm of soil in the erosion terrain before landslide failure. The mass of carbon sequestered in one year by an area, $a_s(t)$, of scars with age t years (assuming a depth of one metre and a bulk density of 1·3 t m^{-3}) is then given by

$$m_s(t) = 1{\cdot}3a_s(t)0{\cdot}03C_{100}e^{-0{\cdot}03t} \qquad (7)$$

The total mass of carbon sequestered by an erosion terrain in one year, M_s (in t yr^{-1}), by scars of all ages may be estimated by integrating $m_s(t)$ over time from $t = 0$ to $t = T$, the time since deforestation (assumed to be uniformly 100 years for every erosion terrain), that is,

$$M_s = \int_0^T 1{\cdot}3a_s(t)0{\cdot}03C_{100}e^{-0{\cdot}03t}dt \qquad (8)$$

The distribution of scar age is assumed to take the form

$$a_s(t) = be^{-k(T-t)} \qquad (9)$$

where b is the yearly area rate of scar production immediately after deforestation (in km^2 yr^{-1}), and k is the 'coefficient of event resistance' for the erosion terrain in question (event resistance is the process by which the area of uneroded land available for erosion diminishes in time as erosion proceeds). NZeem® is used to estimate the annual sediment mass reach-

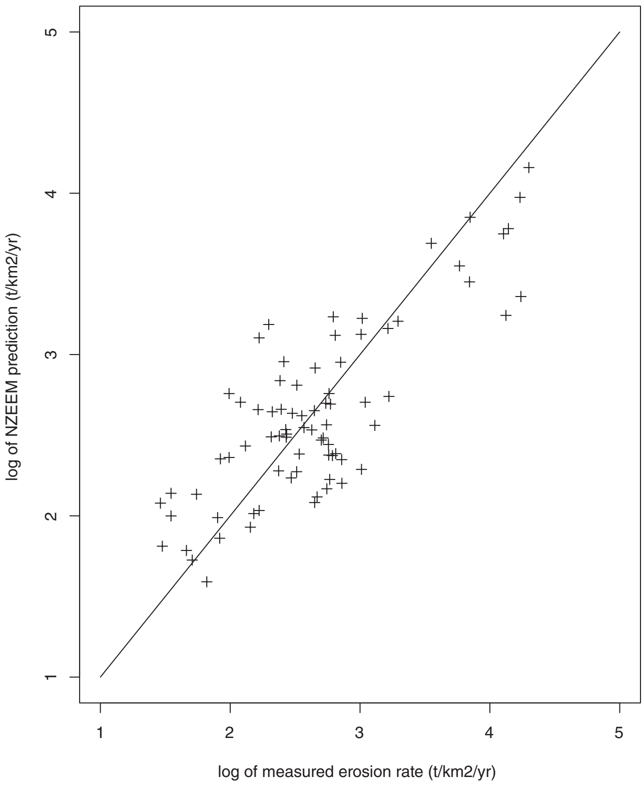

Figure 3. Plot of NZeem® predictions versus measured specific sediment discharge for 80 long-term measurement sites spread throughout New Zealand. The value of R^2 is 0·65.

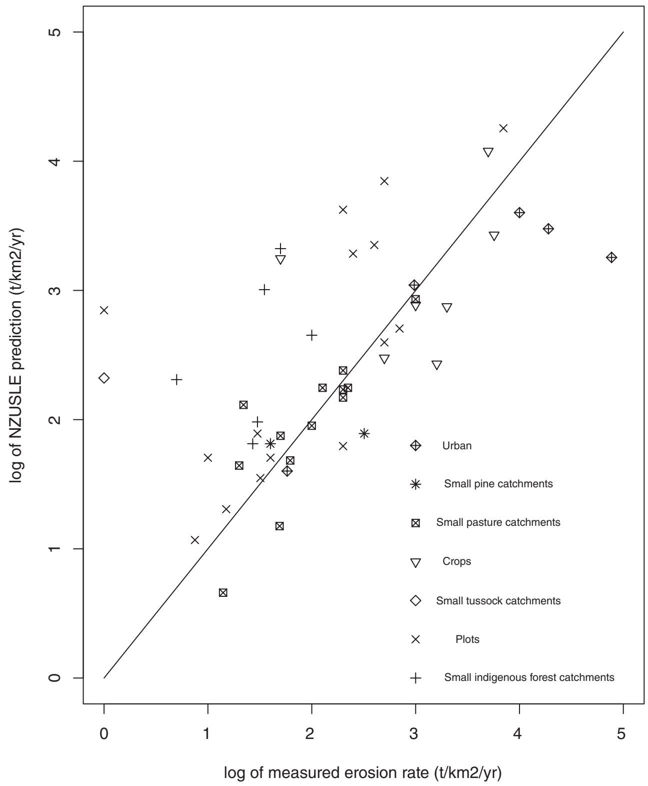

Figure 4. Plot of NZUSLE predictions versus measured rates of surficial erosion spread throughout New Zealand. The value of R^2 is 0·60.

ing streams from landslides, on landsliding erosion terrains, which is adjusted by the sediment delivery ratio (from the HEL model) to estimate *b* (assuming an average scar depth of 100 cm and bulk density of 1·3). If *k* is small it may be approximated by the ratio of *b* over the total area of land available for landsliding (from the HEL model). Equation 9 is substituted into Equation 8 to obtain

$$M_s = 1{\cdot}3bC_{100}\frac{0{\cdot}03}{(0{\cdot}03-k)}(e^{-kT}-e^{-0{\cdot}03T}) \qquad (10)$$

The debris tails remaining on the hillside redistribute carbon on the landscape. They are typically deposited in a layer thinner (~20 cm) than the ~100-cm depth of landslide scar as the fluid debris solidifies (Crozier, 1996; Claessens *et al.*, 2007). The debris tails will have a carbon content of approximately C_{100} as the fluid debris is usually mixed as it travels downslope. The debris tails remaining on the hillsides will begin to sequester carbon to achieve a carbon content of C_{10} at a rate similar to the bare erosion scars (the rate is controlled primarily by the phosphorus content). Assuming the debris tails are not buried by subsequent landsliding, the mass of carbon sequestered by landslide debris in an erosion terrain in a year, M_d (in t yr^{-1}), will be approximately one minus the mean sediment delivery ratio, β, times the carbon sequestered by old landslide scars, that is,

$$M_d = (1-\beta)M_s \qquad (11)$$

There is an implict assumption here that the carbon content of the soil buried below the debris tails changes slowly after burial and contributes little to carbon sequestration/decomposition. In New Zealand there is little data on this. Elsewhere, Stallard (1998) and Harden *et al.* (1999) supported this assumption with the observation of generally enhanced carbon stocks in the deep soils of agricultural lowlands and sedimentary basins. The increased wetness and reduced aeration at depositional sites compared with eroding slopes is thought to slow down decomposition. Indeed, Berhe *et al.* (2007) commented that soil burial in most cases contributes to carbon sequestration because it constitutes transfer of SOC from more active components in topsoil to more passive reservoirs in depositional sites.

Surficial erosion is generally small, in comparison with mass-movement erosion, and so it is assumed that soils undergoing surficial erosion are sequestering carbon at a rate equal to the erosion carbon loss. The mass of carbon sequestered per year in an erosion terrain by soils undergoing surficial erosion, M_u (in t yr^{-1}), is then given by

$$M_u = p_s O \qquad (12)$$

Results

Current carbon budget (year 2008)

The carbon export to the ocean (due to erosion) for the North Island is estimated to be 1·9 million tonnes per year. Six erosion terrains contribute more than 0·10 million tonnes per year to this total: the two earthflow terrains, 6.3.2. and 6.3.3., export 0·25 and 0·24 million tonnes per year; the two gully terrains, 6.3.4. and 7.3.2., export 0·29 and 0·41 million tonnes per year; the hill country on mudstone terrain, 7.3.1., exports 0·13 million tonnes per year; and hill country on sandstone, 7.4.1., exports 0·10 million tonnes per year. The carbon export to the ocean (due to erosion) for the South Island is estimated to be 2·9 million tonnes per year, one million more than the North Island. There are six erosion terrains that contribute more than 0·10 million tonnes per year to the South Island total: active flood plains, 1.1.1., export 0·28 million tonnes per year; non-loess terraces and fans, 4.1.1., export 0·10 million tonnes per year; hilly steeplands in soft-sandstone, 7.1.2., export 0·13 million tonnes per year; mountain steeplands in hard sedimentary rocks, 8.1.1., export, 0·50 million tonnes per year; mountain steeplands in schist rocks, 8.1.2., export 1·40 million tonnes per year; and alpine slopes, 9, export 0·14 million tonnes per year [see Dymond *et al.* (2010) for description of erosion terrains]. The North and South Islands together export 4·8 million tonnes of carbon each year to the ocean.

The sequestration of carbon by soils in the South Island is assumed to be in balance with the carbon export by erosion, that is, 2·9 million tonnes per year. The contribution of individual erosion terrains to this total is the same as their contribution to carbon export. In the North Island, the sequestration of carbon by soils is estimated to be 1·25 million tonnes per year, which comprises 0·65 from landslide scars, 0·3 from debris tails, and 0·3 from surficial erosion sites. The total of 1·25 million tonnes per year is significantly less than the 1·9 million tonnes being exported to the ocean, so there is a current net loss of carbon from North Island soils (due to erosion) of approximately 0·65 million tonnes per year. This net loss occurs primarily in the earthflow and gully terrains where there is negligible sequestration of carbon by soils. On the erosion terrains where landsliding is the dominant erosion process, there is a net increase of soil carbon, for example, the hill country on mudstone terrain, 7.3.1., is sequestering 0·29 million tonnes per year, which is over twice the export.

Figure 5 shows the net sink of carbon for the North and South Islands, and New Zealand in total. There is a net sink of 0·85 million tonnes per year for the North Island, and a net sink of 2·30 million tonnes per year for the South Island, making a total of 3·15 million tonnes per year for New Zealand. This is equivalent to 45% of New Zealand's fossil fuel carbon emissions in 1990 (Ministry for the Environment, 1997). The contribution of individual erosion terrains to the net carbon sink in the South Island follows a similar pattern to that for soil sequestration of carbon, that is, active flood plains, 1.1.1., sink 0·22 million tonnes per year; hilly steeplands in soft-sandstone, 7.1.2., sink 0·10 million tonnes per year; mountain steeplands in hard sedimentary rocks, 8.1.1., sink 0·40 million tonnes per year; mountain steeplands in schist rocks, 8.1.2., sink 1·12 million tonnes per year; and alpine slopes, 9, sink 0·10 million tonnes per year. In the North Island, there are three erosion terrains that contribute more than 0·10 million tonnes per year to the net sink: the hill country on mudstone terrain, 7.3.1., sinks 0·26 million tonnes per year; hill country on sandstone, 7.4.1., sinks 0·18 million tonnes per year; and hill country on greywacke, 7.6.1., sinks 0·10 million tonnes per year.

Historic carbon budgets (years 1010 and 1910)

For comparison with 2008, erosion carbon budgets were also calculated for the year 1910, nominally 10 years after deforestation in North Island hill country, and for the year 1010, well before human-induced deforestation. Figure 6 shows that immediately following deforestation carbon export to the sea (due to erosion) increases from approximately 0·5 million tonnes per year to 1·9 million tonnes per year. Following deforestation, the sequestration of carbon by soils reduces from approximately 0·5 million tonnes per year to 0·25 million tonnes per year, and then increases to 1·25 million tonnes per year by the year 2008 – this is because after deforestation sequestration is driven by the number of landslide scars and it takes time for their numbers to build up. The net sink following deforestation reduces from approximately 0·5 million tonnes per year to 0·1 million tonnes per year, then increases to 0·85 million tonnes per year by 2008.

Discussion

The export of SOC to the ocean from New Zealand (due to erosion) is estimated to be 4·8 million tonnes per year. To estimate the uncertainty of the total carbon export it is necessary to consider systematic errors that persist through all the erosion terrains: random errors tend to cancel out in the summation from 89 erosion terrains (see Appendix). The most important systematic error is the assumption that the carbon concentration of sediment is the same as the soil at the source of erosion. Kuhn (2007) reported that sediment from surficial erosion can have a carbon enrichment of up to 50%. Although enrichments of this magnitude are unlikely for mass-movement erosion, we take a conservative approach and assign a systematic error of +50% and −25% to represent this

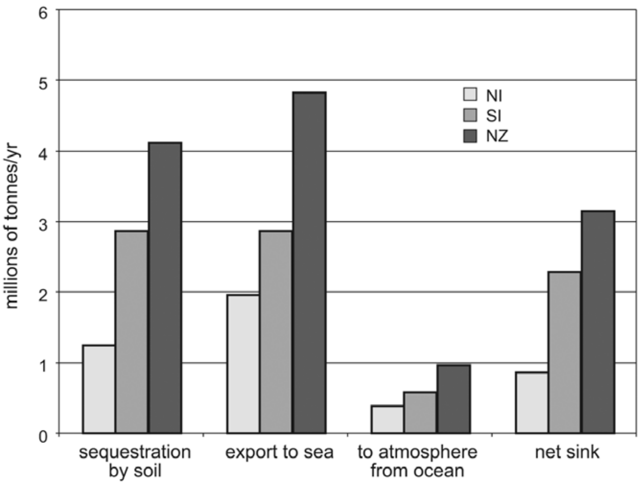

Figure 5. Annual carbon transfers associated with soil erosion for North Island (NI), South Island (SI), and New Zealand (NZ) at 2008.

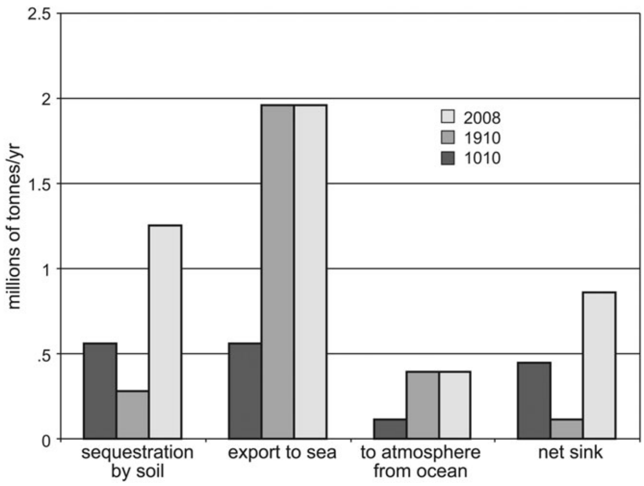

Figure 6. Annual carbon transfers associated with soil erosion for North Island at years 1010, 1910, and 2008.

uncertainty; as well as that associated with change in carbon content of sediment during transport in rivers (this should be small as travel times in New Zealand's steep and generally short rivers are rarely more than several days). So the total export of SOC is given by 4·8 (–1·2/+2·4) million tonnes per year. This is higher than the Scott *et al.* (2006) estimate of 2·7 (±1·0) million tonnes per year of POC exported to the ocean, but the uncertainty ranges overlap. The Scott *et al.* (2006) estimate should be considered more accurate than that reported here because it is based on measurements of carbon content of riverine sediment yield directly, rather than indirectly using carbon content of soils *in situ* with our method. However, the method used in this paper establishes the link between the source of SOC and carbon export, enabling land use to be considered in mitigation options.

Despite a large export of soil carbon to the sea due to erosion, most of this carbon is replaced by sequestration of CO_2 through regenerating soils. In the South Island, all the 2·9 million tonnes of carbon exported to the sea per year are expected to be replaced by sequestration because there have been no major perturbations of the climate or vegetation in the last 5000 years and the landscape will be in approximate equilibrium. However, in the North Island, of the 1·9 million tonnes exported to the sea, only 1·25 million tonnes are replaced by sequestration of CO_2. [The carbon sequestered as a proportion of export broadly agrees with Page *et al.* (2004) who calculated that on mudstone hill country the erosion carbon export per unit area was 1·0 t ha^{-1} yr^{-1} and that 60% of this was sequestered by regenerating landslide scars.] At present, therefore, there is a net loss of 0·65 million tonnes of carbon from North Island soils each year. Most of this net loss occurs in the gully and earthflow terrains. If the gully and earthflow terrains were afforested, thereby reducing erosion rates by an order of magnitude, the net loss of soil carbon in the North Island would be reduced to zero.

Subtracting the soil carbon not buried on the ocean floor (≈ 20%) from the carbon sequestered from the atmosphere by regenerating soils gives a net carbon sink of 3·1 million tonnes per year for New Zealand (due to erosion). Assuming uncertainties of +50% and –25% for the sequestration, and +100% and –50% for the release of carbon from the ocean, the uncertainty of the net sink is approximately +2·5 and –2·0 million tonnes per year. The net sink for the South Island is independent of land use in the lowlands and will continue. The net sink for the North Island would reduce after afforestation of hill country from 0·85 to 0·5 million tonnes per year. Although soil erosion has many negative environmental impacts in New Zealand, it currently has a positive impact on reducing global warming. However, this conclusion should be made with caution because it relies on landscapes being able to regenerate soils at the same rate they are eroded. This is often the case in New Zealand with its high biological productivity, but there are some landscapes where soil erosion exceeds a threshold beyond which soils cannot regenerate and whole landscapes collapse. In some of the gully terrains, major collapses of whole hillsides have already been observed. Indeed, if afforestation, for soil conservation purposes, was targeted on the North Island gully and earthflow erosion terrains alone, after canopy closure of the trees the net sink of 0·85 million tonnes would be increased to approximately 1·35 million tonnes per year.

Results show a net sink of atmospheric carbon due to erosion for New Zealand. This sink is primarily due to a conveyor belt transfer of carbon from the atmosphere to soils and then to the sea floor, where most of the carbon is buried. In the South Island, the net sink is driven by high rates of natural erosion, which are in balance with soil regeneration. In the North Island, the net sink is driven by high rates of human-induced erosion, which are partly balanced by soil regeneration. Either way, it is the high rates of erosion that are driving the net sink as most of the eroded sediment is buried at sea and soils regenerating from erosion sequester CO_2 to replace the lost carbon. Assuming that soil erosion drives a net sink of atmospheric CO_2 the same way for other high-standing islands of the southwest Pacific (Taiwan, Indonesia, Malaysia, Papua New Guinea, and the Philippines), the net sink for these islands would be approximately 80% of the 50 million tonnes per year reported by Lyons *et al.* (2002), that is, 40 million tonnes per year. This is approximately 5% of the global residual sink of carbon (Schimel, 1995).

The analysis in this paper considers the fate of carbon as it moves through the landscape as a result of soil erosion, including rill and inter-rill, as suggested by Kuhn *et al.* (2009). The landscape considered is New Zealand, a high-standing island in the southwest Pacific, which could be regarded as representative of other high-standing islands in that region. The results give support to the contention by Stallard (1998) that there are circumstances satisfied in certain landscapes that give rise to significant sinks of carbon. In this instance, the significant burial of eroded carbon required to give a carbon sink is provided by the high rates of deposition in the marine environment. In other landscapes where most sediment is deposited in the landscape before it reaches the sea, a careful consideration of the fate of that carbon would be required on a spatio-temporal basis before a significant carbon sink could be inferred.

Conclusions

The North Island of New Zealand is estimated to export 1·9 (–0·5/+1·0) million tonnes of POC per year to the sea, and to sequester 1·25 (–0·3 /+0·6) million tonnes of carbon per year from the atmosphere through regenerating soils. The South Island of New Zealand is estimated to export 2·9 (–0·7/+1·5) million tonnes of POC per year, and to sequester approximately the same amount. Assuming exported carbon is buried at sea with an efficiency of 80% (i.e. only a 20% loss through non-burial and decomposition) gives New Zealand a net carbon sink of 3·1 (–2·0/+2·5) million tonnes per year (i.e. approximately 45% of New Zealand's fossil fuel carbon emissions in 1990). This results from a conveyor belt transfer of carbon from the atmosphere to soils regenerating from erosion and to the sea floor where carbon is permanently buried. The large magnitude of the net sink is primarily due to tectonically driven uplift and erosion combined with high biological productivity.

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Appendix: Consideration of Random and Systematic Errors

A national budget of net emission of carbon to the atmosphere from the soil due to erosion processes is given by summing up G in Equation 4 for each erosion terrain

$$\sum_{i=1}^{n} G_i = \sum_{i=1}^{n} D_i + \sum_{i=1}^{n} f_{si} O_i - \sum_{i=1}^{n} R_i \tag{A13}$$

where i denotes the ith erosion terrain and there are n erosion terrains. Consider each term in Equation A13 separately.

The difference between an estimate of D_i and the true D_i , D_i', comprises a systematic error, δ, which is constant for all erosion terrains, and a random error ε_i, which depends on the erosion terrain.

$$D_i = D_i' + \delta + \varepsilon_i \tag{A14}$$

The national sum is then given by

$$\sum_{i-1}^{n} D_i = \sum_{i-1}^{n} D_i' + n\delta + \sum_{i=1}^{n} \varepsilon_i \tag{A15}$$

where n is the number of erosion terrains.

The variance of the national sum may be written as

$$\mathrm{Var}\left(\sum_{i=1}^{n} D_i\right) = n^2 \mathrm{Var}(\delta) + \mathrm{Var}\left(\sum_{i=1}^{n} \varepsilon_i\right) \tag{A16}$$

$$= n^2 \mathrm{Var}(\delta) + n\overline{\mathrm{Var}(\varepsilon_i)} \tag{A17}$$

where the overbar is the mean value of,

$$\approx n^2 \mathrm{Var}(\delta) \quad (\text{as } n \text{ becomes large}) \tag{A18}$$

The coefficient of variation squared of the national sum of D_i is then given approximately by

$$\frac{\mathrm{Var}\left(\sum_{i=1}^{n} D_i\right)}{\left(\sum_{i=1}^{n} D_i\right)^2} \approx \frac{n^2 \mathrm{Var}(\delta)}{(n\bar{D}_i)^2} \tag{A19}$$

$$\approx \frac{\mathrm{Var}(\delta)}{(\bar{D}_i)^2} \tag{A20}$$

Equation A20 shows that the coefficient of variation squared of the national sum of D_i is approximately the coefficient of variation squared of the systematic error. This result also holds for the other terms in Equation A13. So the consideration of errors for a national budget involving many erosion terrains involves primarily the consideration of systematic errors.

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