Title: National contaminant mapping of soil losses from surficial erosion: an analysis of livestock grazing pressures on soil losses across Aotearoa, New Zealand

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Background & Scope:

Soil erosion is a significant challenge for agricultural regions, with cascading impacts to waterways, land productivity, soil carbon, and ecological health. Spatially and temporally explicit models of earth-surface processes are increasingly recognized as one of the greatest opportunities for meeting soil conservation and Sustainable Development Goals (Lefevre et al., 2020; Smetanova et al., 2020). Such models are effective and impactful means for improving understanding of sources and causes of soil loss, and in doing so, we can begin to identify accelerated rates of soil degradation and erosion resulting from agricultural activities (Borrelli et al., 2017; FAO & ITPS, 2015; Smetanova et al., 2020). Recently, advances in modeling have integrated models of livestock grazing with surface erosion process models in order to understand the impact of livestock treading on soil properties and surficial erosion (Donovan & Monaghan, 2021). In doing so, the framework enabled quantitative analysis of the impact of pastoral and intensive forage crop grazing at scales ranging from farms to catchments and beyond.

Herein, we apply this analytical framework to determine the susceptibility of land to physical degradation and surface erosion resulting from landuse pressure across New Zealand. This work supports national efforts focused on meeting both economic (e.g., dairy, beef, and sheep production) and environmental goals (e.g., water quality, land preservation, greenhouse gas emissions) by identifying sediment and contaminant losses from agricultural activity (Ministry for the Environment, 2019a; Our Land and Water, 2018). By understanding areas most likely to contribute to soil loss and degradation, we can minimize the intersection of deleterious grazing activities and erosion-prone areas via proactive decisions rather than reactive strategies. The approach captures the spatial and temporal variability of factors impacting erosion susceptibility using the empirically-based Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997; Wischmeier and Smith, 1978), which has been widely accepted and used for applications spanning field, catchment, national, and even global scales (Borrelli et al., 2017).

Methods & Data:

The methods applied herein were developed to model contaminant losses of sediment across New Zealand that incorporate spatially-explicit estimates of landuse pressure based on grazing intensity. In order to do so, we use a nested-modeling approach that captures both the inherent conditions that impact soil loss (e.g., terrain, soils, vegetation, rainfall) and managed conditions (i.e., grazing pressures) based on novel methods previously developed by the author. The managed conditions include the location, extent, and timing of grazing pressure and are determined through a series of novel geospatial analyses and process-based modeling (Donovan & Monaghan, 2021) that capture the impact of livestock grazing on soil physical properties. The inherent conditions are those that influence the land's natural susceptibility to degradation and soil loss, which are modeled using a geospatial formulation of the Revised Universal Soil Loss Equation (RUSLE) developed for New Zealand (Donovan, 2022).

RUSLE and its predecessor, USLE, predict mean annual soil loss from surface erosion based on a set of equations derived from empirical measurements of soil losses from agricultural plots (Renard et al., 1997).

RUSLE encapsulates seasonal rainfall erosivity (R), slope length (L) and steepness (S), soil erodibility (K), ground cover and management factors (C) (Fig. 1); each of which is considered an important influence on soil loss (Selby, 1993). We include additional precision through calculating seasonally-variable grazing-adjusted ground cover (C_{gr}) and treaded soil erodibility (K_{tr}) for pastoral lands based on Donovan and Monaghan (2021).

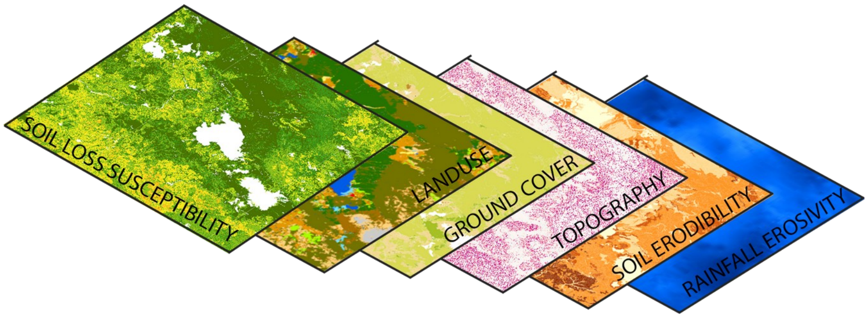

Figure 1. Conceptual RUSLE framework that is used to calculate baseline/inherent soil losses (t/ha/yr), without considering the impacts of livestock grazing on soil properties and ground cover.

Slope steepness (S) seeks to capture the rate of change in soil loss with varying gradients, while slope length (L) accounts for the distance over which a slope gradient occurs. The equations for both S and L have been reformulated for use in geographic information systems (GIS) and are thoroughly summarized and compared (Bircher et al., 2019). Estimates of S and L for New Zealand are improved via the use of enhanced hydrological flow routing and empirical equations describing S and L found in literature. We used a 15-metre digital elevation model (DEM) with seamless coverage of New Zealand, prepared and made publicly available by the National School of Survey at the University of Otago (Columbus et al., 2011). This DEM serves as the data inputs for calculating slope, flow accumulation, as well as the L and S factors. Prior to any calculations of slope steepness and length, spurious features were removed from the DEM to ensure optimal flow routing, though spurious features remain through, floodplains, and wide gravel-bedded rivers.

Table 1. A summary of dataset information used for the RUSLE analysis.

Dataset Name	Year(s)	Spatial Extent	Resolution	Information	Source
Digital Elevation Model	2011	National (NZ)	15 m^2	Slope (degrees)	Otago School of Surveying
LUCAS	2016	National (NZ)	Land use clusters	Grazed dairy and ‘non-dairy’ locations	MfE
Livestock populations	2017	National (NZ)	Hexagonal grids	Dairy, sheep, and beef counts	StatsNZ
NIWA Rainfall	1981-2010	National (NZ)	15m^2 resampled	Average monthly rainfall	NIWA
Fundamental Soils Layer	N/A	National (NZ)	Soil units	Soil physical and chemical properties	MfE
Winter forage crops	2018	National (Lands > 7 degrees)	Paddock-scale	Location, extent, and feed of WFC	Manaaki Whenua
Pastoral farmlands	2018	National	Land unit	Livestock grazing class	Internal

LCDB	2018	National (NZ)	Regional extent	Regional boundary demarcations	LINZ

Soil erodibility is captured in the K-factor, which incorporates physical and chemical properties of soil including fractions of sand, silt, and clay, permeability, structural stability, and organic matter content. Soil characteristics used to calculate soil erodibility (K) factor were derived from the Fundamental Soil Layer (FSL), a free and publicly-available national soil map (Newsome et al., 2008) with physical, chemical, and mineralogical information. Because RUSLE does not incorporate the impact of grazing and treading on soil loss, despite significant impacts to ground cover and soil physical properties, we apply a nested grazing model (Donovan and Monaghan, 2021) to calculate treaded soil physical properties (RUSLE K_{tr}). The model captures impacts to soil physical properties through compaction and pugging coefficients (Fig. 2), which vary spatially and temporally due to differences in soil texture (clay content), soil moisture, and grazing intensity. While grazing impacts vary with soil depth (Greenwood and McKenzie, 2001; Kelly, 1985), we do not capture such differences due to our focus on surface erosion and because no consistent results existed within or across literature.

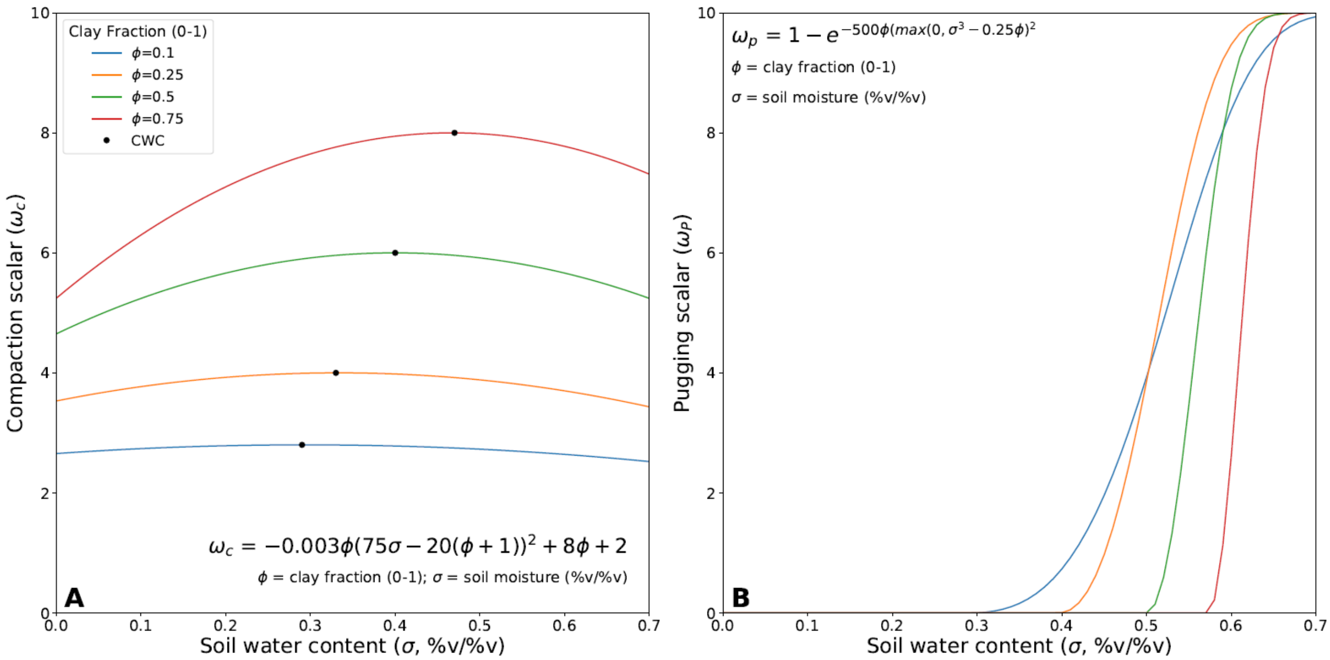

Figure 2. Figures extracted from Donovan & Monaghan (2021). Models of (left, A) compaction and (right, B) pugging susceptibility as a function of soil water and clay contents. (A) For a constant hoof pressure, compaction susceptibility (ωc) peaks as soil water content approaches the critical water content (black points). At lower clay contents (blue line), the variability and magnitude of compaction potential is dampened relative to soils with higher clay content (green and red lines). (B) As soils increase beyond the CWC, plasticity of soils increases along with pugging susceptibility (ωp) as illustrated by steeper slopes beyond the CWC. ωp approaches a threshold as pugging cannot increase indefinitely. Soils with higher clay content are more resilient to pugging than low-clay soils (Greenwood and McKenzie, 2001; Kemper et al., 1987; Zeng et al., 2018) but exhibit more rapid changes in resilience for each increase in SWC beyond the CWC (Finlayson et al., 2002).

The cover and management factor (*C*-factor) is used to estimate the effect of canopy and ground cover, as well as land use management, in reducing surficial soil loss (Wischmeier and Smith, 1978). Land cover is represented using three geodatabases: the Land Use and Carbon Analysis System (LUCAS, 2016), the New Zealand Landcover Database (LCDB, 2018) version 5, and the 2018 winter forage crop layer (Belliss et al., 2019). The LCDB provides national coverage, and distinguishes 33 distinct landuse classes. Winter forage crops are not included as a class of land cover, but are an important cover class in the implementation of RUSLE (Donovan, 2022; Donovan and Monaghan, 2021). Thus, winter forage paddocks as mapped by Bellis et al.,

(2019) were added to the landcover layer, and a unique factor C_{Grazed} was derived for winter forage paddocks, as well as grazed grasslands. To determine the extent and location of grazed land, as well as estimates of livestock type and population, we derived a pastoral geodatabase based on an inverse modeling approach. Grazed lands identified based on the union of grazed lands identified in both the LCDB, LUCAS, and the pastoral geodatabase, which were then merged with the StatsNZ livestock numbers hexagonal grid geodatabase. The StatsNZ geodatabase also provided stocking densities for each hexagon is 346 km^2 (34,600 ha), but these were not used because they assume livestock are distributed evenly across the entire hexagon, without considering non-pastoral and ungrazed lands within each polygon. This results in an underestimation of stocking density, except where 100% of the land within a polygon is grazed. Within grazed pastoral lands, the pastoral geodatabase was used to parse specific farm types, and the estimated population counts of livestock were assumed to be distributed uniformly across grazed farmlands.

Rainfall erosivity (R) captures the kinetic energy potential of rainfall that drives soil erosion by water (Klik et al., 2015). Mean monthly rainfall grids based on New Zealand rainfall records spanning 1981-2010 (NIWA, 2012; Tait et al., 2012) were resampled using nearest neighbor interpolation from 100-m to 15-m resolution to align with the 15-m DEM. The 30-year rainfall data thus reflect the central tendency of each month's long-term conditions. Monthly grids were summed to calculate seasonal rainfall totals for Spring (September – November), Summer (December – February), Autumn (March - May), and Winter (June – August). Thus, the erosive force of rainfall represent the ensemble tendency of conditions that are likely to prevail over yearly variability and anomalies. For more details on the calculations of R, see Donovan (2022).

Because RUSLE does not incorporate the impact of grazing and treading on soil loss, despite significant impacts to ground cover and soil physical properties, we apply a nested grazing model (Donovan and Monaghan, 2021) to calculate treaded soil physical properties (RUSLE K_{tr}) and grazed ground cover (RUSLE C_{gr}). The grazing model uses empirical relationships between grazing/treading intensity (i.e., stock hoof pressure, grazing density, duration and history) and damage to soil physical properties (i.e., permeability and structure) and further account for susceptibility due to clay content and soil moisture (Donovan and Monaghan, 2021).

The final modeled values of inherent (ungrazed) surface erosion (E_s, Eq. 1) and grazed surface erosion (E_{gr}, Eq. 2) were calculated as the product of all factors. Values for R, C, $C_{s\text{-}gr}$, and $K_{s\text{-}tr}$ vary seasonally whilst values for K, L, and S remain constant throughout the year. Annual surface erosion is then calculated as the sum of all seasons (Eq. 3). Modeled surface erosion rates are expressed in units of metric tons hectare^{-1} year^{-1} or metric pixel^{-1} year^{-1} unless otherwise stated.

$$E_s = R_s * K * L * S * C_s \qquad \text{Eq. 1}$$

$$E_{s-gr} = R_s * K_{s-tr} * L * S * C_{s-gr} \qquad \text{Eq. 2}$$

$$E_{ann} = E_{Spring} + E_{Summer} + E_{Autumn} + E_{Winter} \qquad \text{Eq. 3}$$

Based on previous and ongoing work (Donovan and Monaghan, 2021, Donovan, 2022, Neverman, Donovan, Smith, et al. In Review), we chose a sediment delivery ratio of 0.25, so that 25% of the sediment is assumed to reach waterways. The results of two previous national analyses demonstrated that this assumption vastly improved estimates of soil loss from pastoral lands (Donovan and Monaghan, 2021), as well as across a range of catchments and other landuses (Donovan, 2022). Most recently, comparisons with sediment yields from REC2 watersheds (Neverman, Donovan, Smith, et al., in review) showed that approximately 85% of New Zealand catchments aligned with this assumption. As such, we do not further validate the results, and suggest future field and catchment-scale multi-year studies across regions and landuses be used to evaluate the magnitude of soil losses, which are based on long-term average rainfall conditions. Thus, model outputs should not be expected to capture every year precisely, but can be expected to lie within the range of variability measured over a 3-5 year period of typical conditions. The soil loss susceptibility results modeled across space are robust and can be considered highly precise in respect to their relative contributions across the catchments. For in-depth descriptions and analyses of the models summarized above, see Donovan & Monaghan (2021) and Donovan (2022).

Results & Discussion

Soil erodibility (K_{factor}) and treaded soil erodibility (K_{tr}) respectively reflect the inherent and treaded erodibility of the soil without accounting for changes in the other RUSLE subfactors (R, C, LS). Changes in soil erodibility (delta-K_f) reflect degradation of the soil physical structure due to compaction and pugging. The soil erodibility exhibits strong variability within and across farm types, as well as across feed types (Fig. 3b). Within each feed type, the variability in soil degradation (e.g., Fig 3b., delta-Kf, y-axis) reflects the combination of underlying soil properties as well as the estimated livestock density. The results generally align with expected trends; where higher-yielding winter forage crops generally had greater grazing densities. Further, strong multivariate relationships exist between grazing intensity, soil texture, and soil degradation (Fig 3b). These results demonstrate the importance of not only grazing intensity, but the inherent properties of the soils underlying such intensive grazing. Clay soils with poorly drained subsurface layers (5-10 cm) exhibit rapid increases in soil degradation for each incremental change in grazing intensity compared to silty and loamy soils with relatively greater drainage properties (Fig. 3b).

For the first time, highly-granular (farm-scale) estimates of livestock types and grazing densities were incorporated into a national-scale model of surficial erosion soil loss susceptibility. Whereas previous approaches utilized broad-scale assumptions of grazing densities for pastures and winter-forage crops, the improved methodologies capture grazing pressures at high-resolution. Further, additional analyses and previous uncertainty analyses (Neverman, Donovan, Smith, et al., in review; Donovan, 2022) confirmed the use of a 0.25 sediment delivery ratio (SDR). In doing so, soil loss from surficial erosion and the contributions to waterways are more robust and reflect the spatial variability surficial erosion susceptibility from both inherent and management factors.

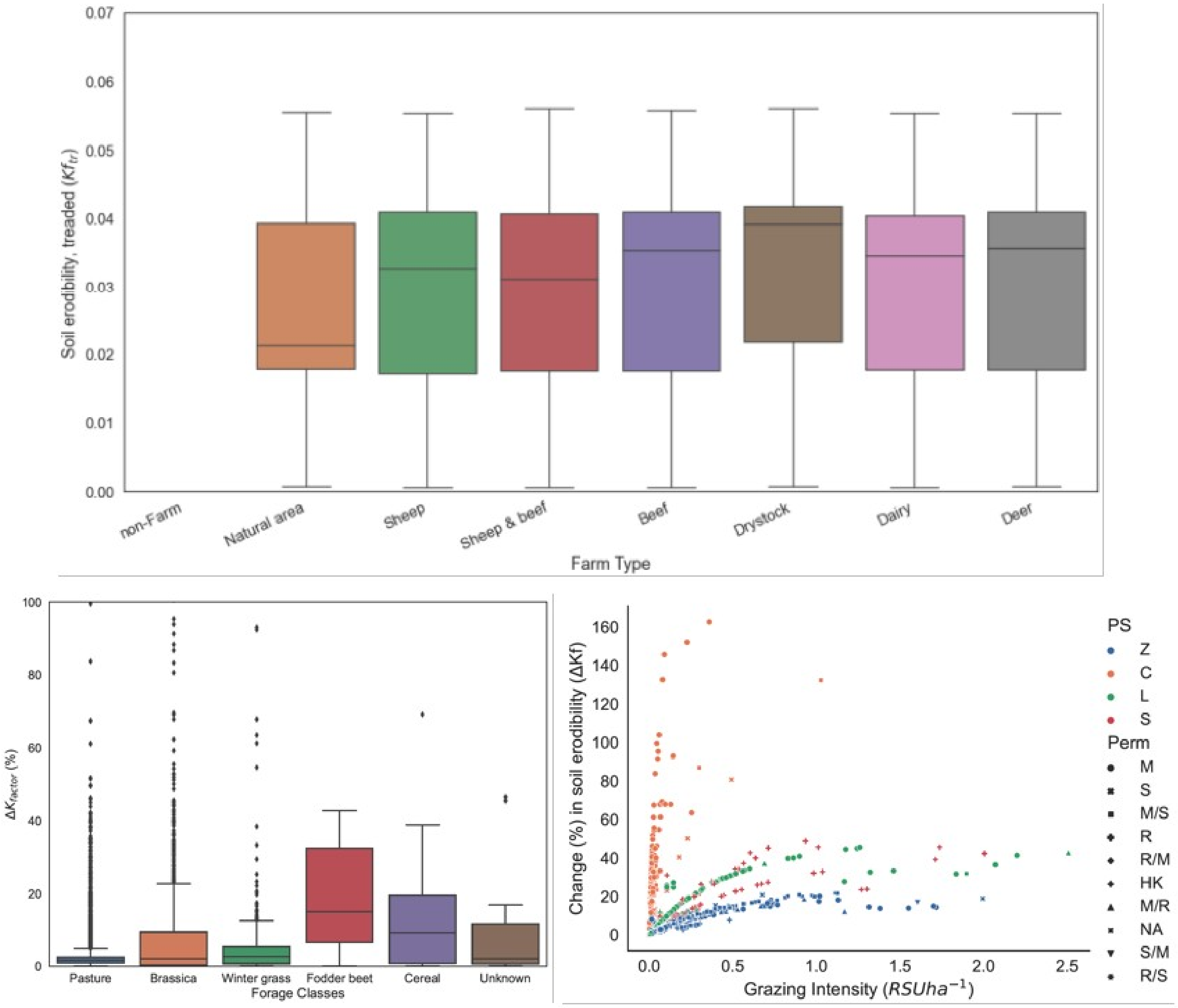

Figure 3: (A, top) Distribution of soil erodibility, treaded (Kf-tr) across each farm type, for all lands across New Zealand. Of note, natural grazed areas generally exhibited the lowest average Kf value. This is equivalent to a higher resistance to erosion (lower erodibility). On the other hand, drystock farms exhibited the highest erodibility. The results in 3A reflect the ensemble interactions between soil properties and grazing intensity throughout the year. (3b, bottom left) The change in soil erodibility (delta-Kf) as a result of grazing, with each hue reflecting different feed types. (3C, bottom right) The change in soil erodibility (delta-Kf) plotted against grazing intensity (x-axis), with different hues and symbols reflecting differing soil textures and drainage rates). S = Sand, Z = Silt, C = Clay, L = Loam. See the Fundamental Soil Layer descriptions of permeability/drainage classes.

Across the various landuse categories, winter forage-crop paddocks have the highest rates of surface erosion, which reflects the combination of extreme bare ground exposure and impacts of damaged soils. The only areas that rival, and exceed in some cases, the rates of winter forage crop paddocks are exposed landslides, which are an end member in terms of exposed, unconsolidated sediments that are readily erodible. Forestry also demonstrates substantially elevated rates of soil loss compared to natural forest due to the periods of nil to minimal exposure post-harvesting. The rates presented are based on an average over a 30-year harvest cycle. Additional information on the calculations of ground cover for this period can be found in Neverman, Donovan, Smith, et al. (in review). Analysis of soil loss rates of scrub/shrub areas indicate that such land covers often exist in areas with extreme rainfall intensities and high slopes, and thus inherently have a high susceptibility to soil loss. In contrast, natural and pastoral grasslands generally exist on low to moderate-slopes with more resilient soils and relatively favorable rainfall conditions. Further discussion of their relative contributions to sediment yields are presented subsequently.

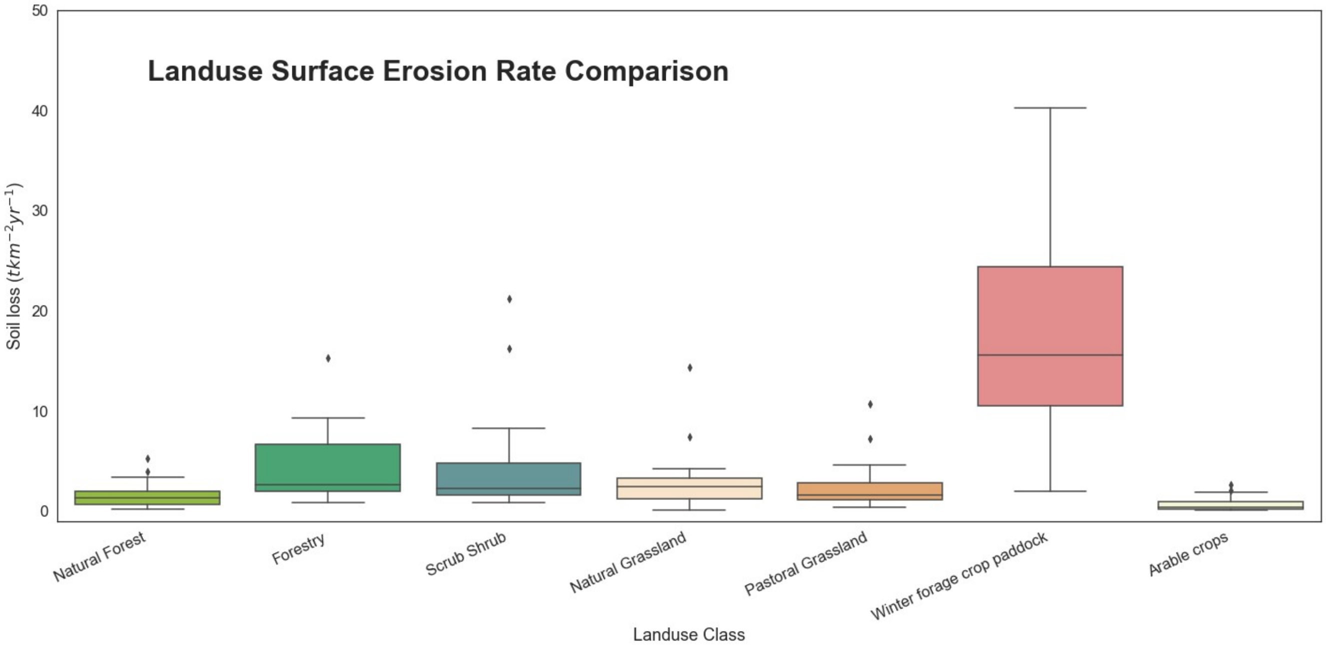

Figure 4: Variability in rates of soil loss from surficial erosion, parsed by broad land use classes. Rates reflect the combined impact of rainfall, soils, ground cover, slope, and flow accumulation.

Two catchments- the Waikato and the Clutha- are used to illustrate soil loss variability across catchments, as well as the relative contributions of each land use/cover class to soil losses within each of these catchments. As urban areas, bare rock, and beaches/dunes are either not subject to surficial erosion or are outside the domain of RUSLE modelling, they are not considered in the ‘erodible land area’ in this analysis. The Waikato catchment’s erodible landuse area is predominately pastoral grasslands (58%), followed by natural/native forests (21%) and forestry (17%), with the remainder (4%) consisting of shrub/scrub, cropland, exposed landslides, winter forage crops, and natural ungrazed grasslands. Pastoral grasslands contribute similar proportions of soil loss (59%) compared to the proportion of land they account for within the catchment. This is approximately a 1:1 ratio of land area to soil loss contributions. In contrast, forage crop paddocks consist of < 0.1% of land area, but contribute over 2% of soil losses, reflecting a 10:1 (10-fold higher) ratio of soil loss to land area occupied. This indicates a disproportionate contribution of sediment from forage crop paddocks. At the other end of the spectrum, natural/native forests occupy over 20% of the land area, but contribute 15% of soil losses. This is a 1:1.3 ratio of erosion to landuse area, and indicates a relatively low impact land class. In between these end members is forestry, which accounts for 17% of land cover and contributes 22% of soil loss from surficial erosion. This suggests that despite high ground cover for part of a 30-year cycle, forestry lands may contribute substantial proportions to long-term sediment loads due to the exposed conditions in the years following a harvest.

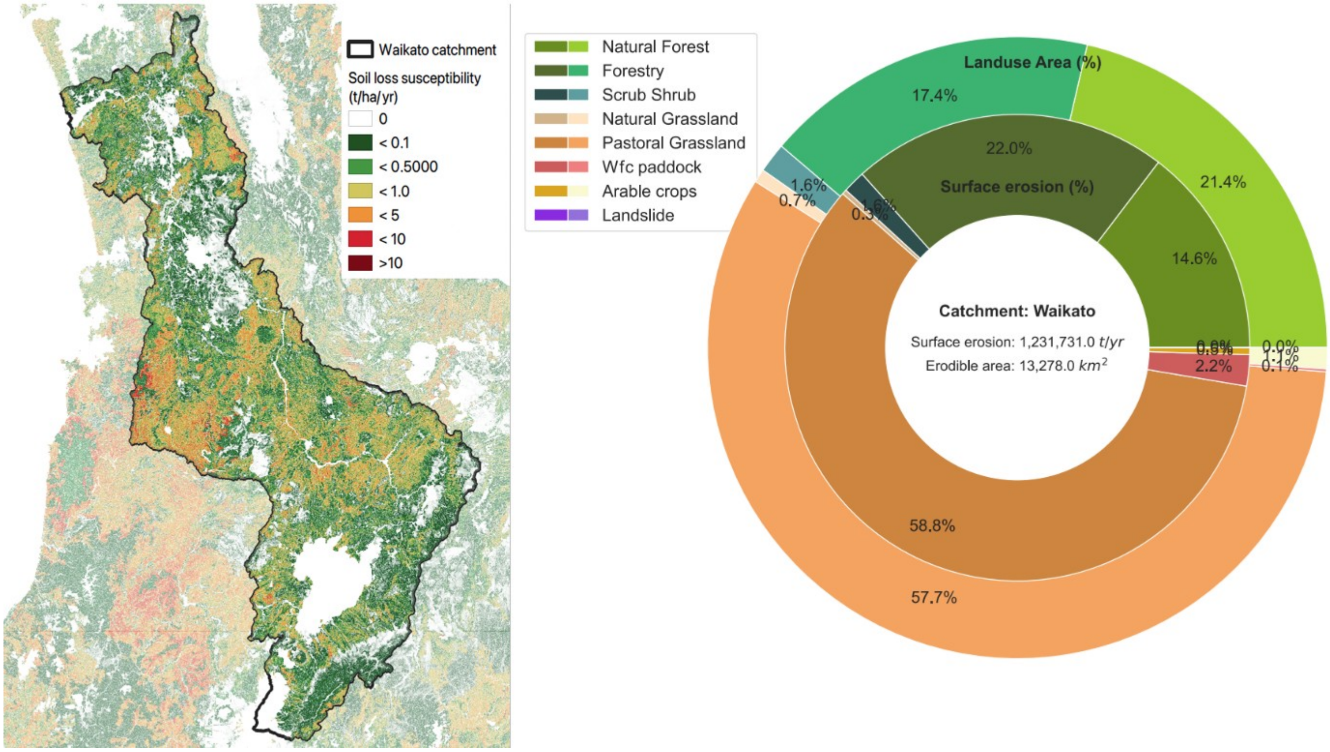

Figure 5: Waikato catchment soil loss summary. (A, left) Waikato catchment spatial distribution of soil losses from surficial erosion (t/ha/yr). (B, right) Distribution of area and relative soil loss contributions from each land use and land cover class. The area and soil loss contributions from surficial erosion are approximately the same. Natural forests have a lower ratio of soil loss to area, whereas forestry generates higher soil losses relative to the area of land surface those activities occupy. In the most extreme case, forage crop paddocks reside on < 0.1% of land, but contribute over 2% to soil losses. This reflects the anomalously high rates of soil loss.

The Clutha catchment provides another demonstration of the variability that can be seen in land use distributions and their contributions to soil losses within a catchment (Fig. 6). In this case, pastoral grasslands occupy 44% of erodible land area, but only contribute 29% of surficial erosion (1:1.5 ratio). This likely reflects a combination of lower rainfall erosivity, lower soil erodibility and relatively lower grazing intensity compared to the Waikato catchment. Another unique attribute is the relatively high surficial erosion contributions (53%) from ungrazed natural grasslands, which only occupy 35% of the catchment's erodible land. Previous analysis for similar regions of the South Island, as well as in Europe, demonstrated that this landuse class is often located at high elevations on steep lands with highly erodible soils. Because they are extremely low productivity, such grasslands are often left ungrazed, and should remain so to avoid exaggerating their soil losses. In this case, again we see relatively high contributions from winter forage crop paddocks, as well as landslides. While their contributions to surficial erosion remain low at the catchment scale, landslides contributions to sediment loads during and after mass movement events are known to contribute substantially to sediment yields over long timescales (Neverman, Donovan, Smith, et al., in review).

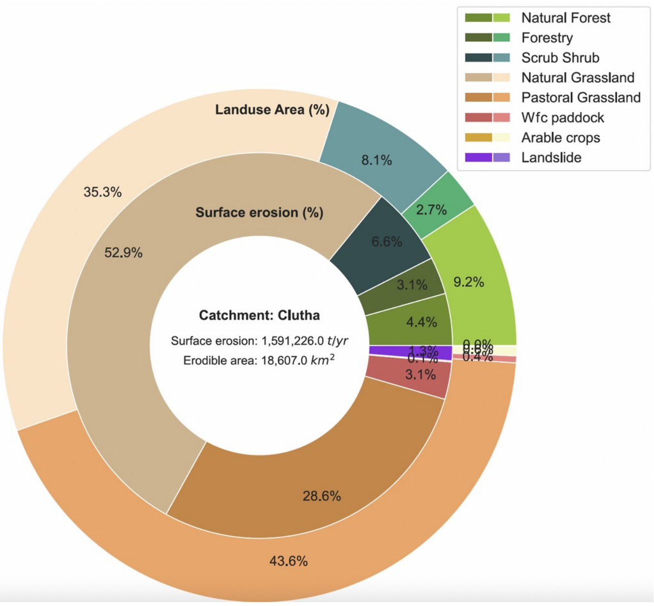

Figure 6: Clutha Watershed distribution of land use and soil loss from surficial erosion. Outer ring with lighter hues reflects landuse proportions will the inner-ring represents surficial erosion relative contributions

We use an undisclosed area of New Zealand to illustrate the impact of winter forage crops on surficial erosion and soil degradation (e.g., Fig. 7 orange and red hues, black bounding boxes), which are hotspots of surficial erosion despite their small spatial extent and temporal window of a single season. In this particular example, the proximity of forage crop paddocks to the river result in additional likelihood that the overwhelming majority of soil lost will end up in the river and downstream waterbodies. In contrast, pastoral lands occupy a large land area, but due to the low grazing pressures throughout the remaining seasons, the rates of soil loss are modest.

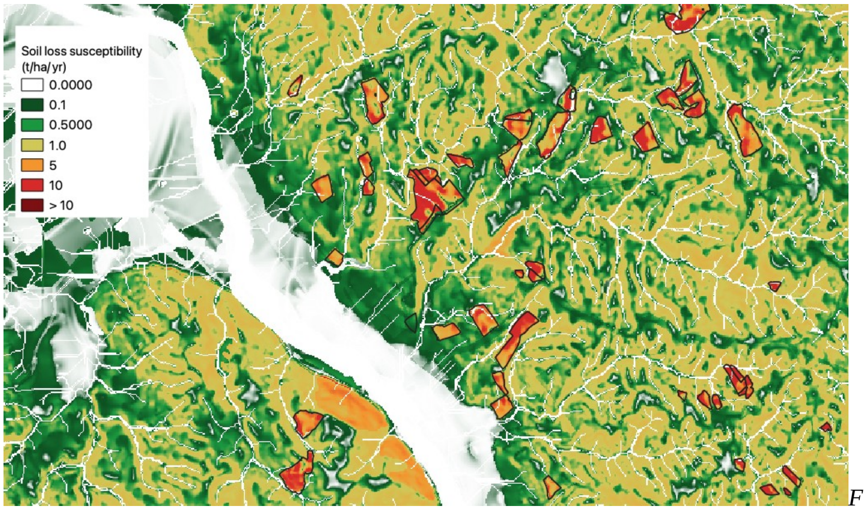

Figure 7: Soil loss map of an undisclosed area with forage crop paddocks. The paddocks (black bounds) are found along the river corridor and up into the nearby hillslopes. The 'hotter' hues of orange and red reflect increasing soil losses compared to greens and yellows. In this case, white areas are dominated by fluvial erosion and thus, are outside the scope of RUSLE modeling.

Summary & conclusions

For the first time, a national-scale soil loss model of New Zealand has captured both inherent landuse properties, alongside high-resolution calculations of livestock grazing densities and landuse pressures. The model captures spatial and temporal variability in soil loss rates (t ha^{-1} yr^{-1}) at high resolution (15-m^2) and seasonal time steps. Soil losses from surficial erosion are modeled using a novel geospatial version of the Revised Universal Soil Loss Equation (RUSLE) as well as a nested-physical grazing model to capture changes to soil properties from treading. The soil losses are calculated as a function of seasonally-variable rainfall erosivity, ground cover, soil properties, grazing practices, and constant terrain information. We note that the modeling captured herein reflects long-term rainfall and landuse conditions, and thus does not capture year-to-year variability. The outputs should compared to field data measured over several years or long-term monitoring sites, such as the comparisons found in previously published modeling work for New Zealand (Neverman, Donovan, Smith, et al., in review; Donovan, 2022; Donovan & Monaghan, 2021). This will vastly improve the ability to draw robust and sound inferences for highly granular areas of interest.

The analyses demonstrate the variability in soil degradation and soil loss rates from different land uses, farm classes, and catchments across New Zealand. Collectively, the results from soil degradation analyses demonstrate the importance of not only grazing intensity, but the inherent soil properties and slopes underlying such intensive grazing. Using illustrations and analysis of the relative contributions of soil losses from various land use classes within two catchments- the Clutha and Waikato- we highlight how soil losses from land use classes are not uniform. These analyses generally indicate that broad and sweeping statements about specific landuse classes are generally unfounded unless specific context and conditions are met. Exceptions to this are forage crop paddocks, landslide scars, and to a lesser degree, exotic forestry land, which had relatively high surficial erosion rates. While landslide's contributions to surficial erosion remained low at catchment scale, their contributions to sediment loads during and after mass movement events are known to contribute substantially to sediment yields over long timescales (Neverman, Donovan, Smith, et al., in review). We conclude that an individual forage crop is not a significant contributor to overall sediment yields when considered at catchment scales due to it's relatively small area, but the conditions of these paddocks are such that even if 1% of lands were forage crops they could account for 10-20% of surficial erosion across the catchment. Thus, when considered as a whole, winter-forage crop paddocks represent a 'low hanging fruit' when considering options for reducing sediment loads in catchments.

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