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Soil disturbance and salinisation on a vineyard affected by landscape recontouring in Marlborough, New Zealand

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ABSTRACT

This paper investigates the effects of landscape recontouring on soil morphology, topsoil organic matter, and soil and water salinisation on a vineyard site in the NE South Island, New Zealand.

Soil pits in representative locations in the virgin and recontoured landscapes were opened for profile comparison, in addition to hand auger transects across infilled gullies and topsoil pit sampling. Disturbed soils exhibited a simplified profile form compared to undisturbed virgin soils, leading to reclassification. Soil mixing in disturbed profiles resulted in more even distribution of some total exchangeable bases compared to virgin profiles. No significant differences in topsoil organic C and N were found between recontoured and virgin landscapes, and the spatial variability was less in the recontoured landscape. Diffuse throughflow in infilled gullies was found to be causing accumulations of salts in an irrigation pond to levels likely to be negative for viticulture. Immediate negative effects for viticulture in the disturbed soil appear to be low, as ersatz soil profiles were reconstructed after recontouring had taken place and the topsoil was well preserved. As this process is widespread in the region, concern is primarily for salinisation potential of throughflow and receiving waters.

1. Introduction

Anthropogenic landscape alteration is largely attributed to increases in agricultural production (Certini and Scalenghe, 2011; Ruddiman and Ellis, 2009). Widespread anthropogenic soils, defined as "soils that have been made by the direct action of people…" (Hewitt, 2010), have been found and dated commonly to c.2000 years and up to c.5000 years before present (Certini and Scalenghe, 2011). It is now recognised that mankind's imprint on the pedosphere has been profound, and owing to the heterogeneous nature of anthropogenic soil alteration, this area of study is one of the next major fields of soil science to be explored (Richter, 2007). Soil disturbance due to increased intensification of viticulture has been described in many northern Mediterranean countries such as Spain, Portugal, France, Italy, and Greece (Kosmas et al., 1997; Ramos et al., 2007). Recent (post 2000) vineyard establishment in NE Spain has involved land levelling and associated terracing work which has been carried out to increase site suitability for mechanisation (Ramos and Martínez-Casasnovas, 2007).

The earthwork processes required to carry this work out have resulted in topsoil layers being removed, mixed, or buried in deeper soil horizons. Resulting soils were low in organic matter, had weak structural properties, and high susceptibility to sealing (Ramos et al., 2000). Related studies have found that soil sealing causes negative effects on the erosion on similar sites (Meyer and Martínez-Casasnovas, 1999; Ramos et al., 2000; Singer and Le Bissonnais, 1998). Deterioration of soil properties such as organic matter, hydraulic conductivity, water retention, and aggregate stability has been reported as a result of vineyard terracing in Spain (Ramos et al., 2007).

The wine industry in New Zealand has grown significantly over the period of 2000–2010 (wineinf.nzwine.com/statistics). The Marlborough region is situated in the north-east South Island of New Zealand and was one of the regions of major viticultural expansion. The region now hosts in excess of 20,000 ha of grape vines dedicated to wine production. Easily-planted valley floors were the first locations to have vineyards established in this region. Many of these plantings occurred during a period of increasing grape prices (statistics from nzwine.com). As land on valley floors became scarce and expensive, it became more economically viable to plant vineyards on rolling hills adjacent to the river floodplains. To make vineyard establishment easier on these hills, especially with regard to mechanisation, an earthwork process known as recontouring was commonly employed. This process commonly utilised a 'double stripping' technique similar to that used in some aluminium mining operations (Koch, 2007). Double stripping typically involved scraping and collection of topsoil and the upper 30 cm of subsoil into separate piles, followed by recontouring of any remaining subsoil and the underlying bedrock to achieve a lower slope gradient. The piles

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were then re-spread into an ersatz soil profile over the recontoured landscape. Topsoil residence in piles has been shown to temporarily decrease soil microbial abundance and alter population structure (Banning et al., 2008; Harris and Birch, 1989), in addition to changes to soil physical properties such as amount of large aggregates (which decrease) (Schäffer et al., 2007). The aesthetic impacts of recontouring on the vista of the landscape is recognised globally (Daniel, 2001; Hunziker and Kienast, 1999), but has not been addressed in the scope of this work.

The aim of this study was to investigate whether or not the recontouring process has led to the deterioration of soil quality on a hilly vineyard site in Marlborough, New Zealand. We hypothesised that (I) stripping, stockpiling, and respreading of topsoil would result in loss of organic C, and (II) that mixing of sodic subsoils and saline bedrock into subsoils would lead to enhanced sodicity and salinity. The objectives of the study aimed at testing these hypotheses were: (i) characterising the effects of recontouring on soil morphology and chemistry; (ii) quantifying and comparing profile masses of organic C and N between recontoured and virgin areas; and (iii) quantifying the enhancement of salinity in zones of drainage accumulation within soils and receiving waters.

2. Methodology

2.1. Study area and field characteristics

The study site was located on a commercial vineyard in the Awatere Valley sub-region of the Marlborough region in New Zealand. The Awatere Valley in the north-east of New Zealand's South Island (see Fig. 1) occupies a fault-angled depression oriented northeast/southwest along the Awatere Fault, which is a component of the larger Marlborough Fault System. This region is active tectonically as it is close to the convergence of the Australian and Pacific plates, and is characterised by high rates of crustal deformation and uplift (Rattenbury et al., 2006). The climate of the lower Awatere Valley is characterised by relatively high sunshine hours (2200 h/year) and a moderate rainfall (620 mm/year) which is distributed towards winter surplus and summer demand for irrigation (NIWA CliFlo, 2013). A scoping study recognised 18 different vineyard sites in the Awatere Valley that have been affected by recontouring (Lynn, 2009). One of these, the Hardcase vineyard, was selected for field work.

Hardcase vineyard comprises 34 ha planted in wine grapes, although the 18 ha highlighted in Fig. 2 identifies the recontoured study area only. The previous site vegetation was mixed dryland ryegrass (*Lolium perenne*)/browntop (*Agrostis capillaris*). The Hardcase property is within an erosional hilly landscape developed in the Miocene to late Pliocene Starborough Formation. This Formation comprises poorly bedded brownish-grey fossiliferous sandstone and sandy siltstone (Rattenbury et al., 2006). The main drainage network on the property is oriented south to north and terminates at the SW–NE trending Blind River to the north of the property. According to the New Zealand Soil Classification System (Hewitt, 2010), the soils on Hardcase vineyard are Argillic Sodic Fragic Pallic soils in the New Zealand Land Resource Inventory database (Landcare Research, 2013). Accessory properties of Pallic soils, some of which may be relevant to recontouring, include high slaking and dispersion, slow permeability (often due to dense subsurface layers), and a perched water table. Inclusion into the Argillic group of Pallic soils is on the basis of a clay-enriched B horizon with evident

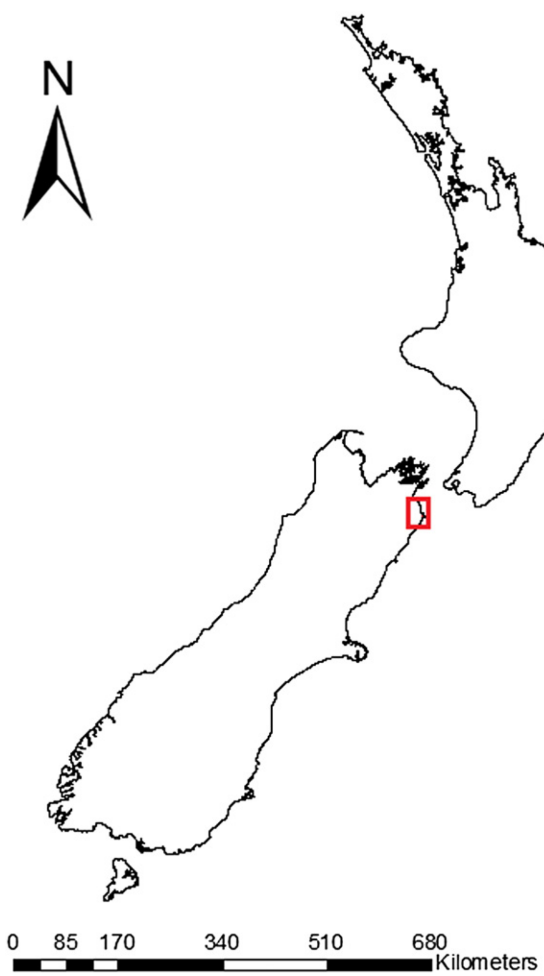

Fig. 1. The study site area in the context of New Zealand.

Fig. 2. Hardcase study site. The area in blue is the recontoured area. Image © DigitalGlobe 2013, from © Google Earth, 2013.

clay coatings on ped or pore surfaces. Inclusion into the Sodic subgroup results from sodic features (Exchangeable Sodium Percentage > 6%) in or beneath the Argillic horizon. Argillic Sodic Pallic soils, which this site is mapped as, equate to Typic Natrustalfs or Haplustalfs under the USDA Soil Taxonomy (Soil Survey Staff, 2010). Recontoured soils are not well accommodated by the USDA Soil Taxonomy, but key out to Typic Ustorthents. The vines on the studied section of this property were oriented E–W (south end) and N–S (northern block).

The recontouring sequence on this vineyard involved the scraping of topsoil and clay (subsoil) into piles, followed by subsequent 'mining' of clay and siltstone from ridge crests and its redistribution to gullies and other low points in the landscape. Subsequently, subsoil was added back to the recontoured land followed by the topsoil to reconstruct the soil. Before planting in grape vines the land was subsoiled (deep-ripped) to a depth of 800 mm. This work was carried out in the summer of 2007, followed immediately by vineyard establishment.

2.2. Field sampling

Soils were described as 'disturbed' if they were present in the recontoured landscape, whereas control soils were described as 'virgin' and occurred on undisturbed hillslopes on the property. Soil pits were excavated on lower and upper slope virgin and recontoured sites to 1–1.2 m depth, and were sampled on a horizon or depth (where horizonation was weak) basis for pH, TEB, and EC. The depth increment sampling basis typically proceeded in 20 or 30 cm increment depths. All pH and EC samples were analysed in duplicate. Soil morphology was described by the methods of Taylor and Pohlen (1962).

The effect of recontouring on topsoil thickness and quality (organic C and N %) was investigated by using sample transects. Six transects were aligned across ridge crests above the recontoured vineyard, and an additional six transects were established across the recontoured section of what was originally the same ridges (Fig. 3). Along each transect, five samples were taken in the sequence footslope–backslope–summit–backslope–footslope from one side of the ridge crest to the other. Sample separation was generally 20 m intra-transect. Slope transects therefore were roughly 100 m in length and consisted of two footslope pits, two midslope pits, and one summit pit per transect. The variation in this 20 m separation was due to differing distances between slope elements on different transects. Sampling involved digging a small pit to the bottom of the topsoil, recording topsoil depth, taking an intact core for bulk density determination, and collecting soil for the analysis of C and N concentrations. Topsoil C and N masses were calculated as follows: $X = [x]\, h\, \rho_b * 100$, where X = C or N profile mass (g m^{-2}), [x] = C or N concentration in %, h = topsoil thickness (cm), and ρ_b = topsoil bulk density in g cm^{-3}.

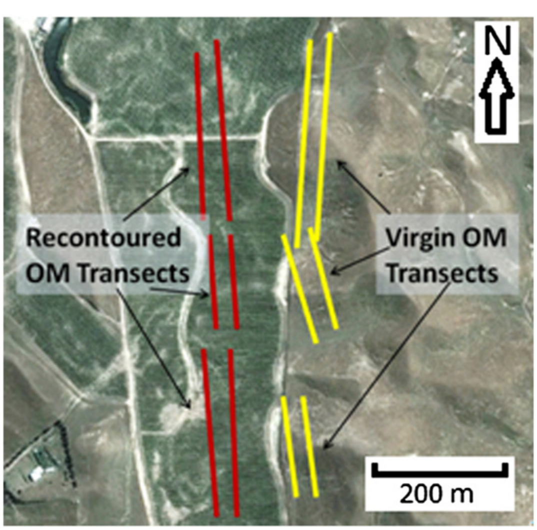

Fig. 3. Organic matter transect locations (approximate; not indicative of exact length and shape of transects). Image © DigitalGlobe 2013, from © Google Earth, 2013.

Examination of a pre-recontouring satellite site image (Fig. 4) indicates the previous drainage networks which may now route subsurface water and solutes as throughflow within gully fills. A transect sampling scheme was designed to identify remobilisation of salts along potential subsurface flow lines inherited from the pre-recontouring topography. Transect location and orientation were informed by conducting stream order analysis of a 25 m resolution digital elevation model of the study area in ArcMap 10 (ESRI, 2012), which captured pre-recontouring topography. Transects were aligned orthogonal to two infilled drainage gullies, hand augered at 10 m intervals, and sampled at 20–30, 40–50 and 70–80 cm depths and analysed for pH and EC. Transect 1 traversed an ephemeral (zero-order) drainage gully, identified by aerial photography pre-recontouring, whereas Transect 2 traversed what was the primary drainage gully. Transect 3 was carried out across a recontoured hillslope which had no pre-existing or current gully. Statistical analyses were carried out by selecting each auger as either 'gully' or 'non-gully' dependant on proximity (± 10 m) to infilled gullies (based on pre-recontouring aerial photos). Mean values were obtained for each auger hole and analysed statistically as described below. Siltstone on this property was found to have a pH of 8.6 and EC of 660 μS/cm. All pH and EC samples were analysed in duplicate. Other techniques including remote sensing, proximal sensing, and modelling have been found to be useful in the prediction of soil surface hydrology and assessment of salt-affected soils but were not included in this work due to time constraints (Farifteh et al., 2006; Schmugge et al., 2002).

An irrigation pond formed by the damming of the main stream draining the vineyard was sampled for water chemistry. Samples were taken on a monthly basis by collection from the pond shore and frozen until analysis could take place. The irrigation pond would have been well mixed due to shallow (roughly 3–4 m) depth. Water samples were analysed for pH and EC as detailed below.

2.3. Laboratory analysis

Soil samples were air dried, crushed, and sieved (brass sieve) to <2 mm particle size (Theng, 1980), except for C and N analyses which were sieved to <63 μm. Total exchangeable bases were determined by the silver-thiourea soil extraction method (Theng, 1980). The extract was analysed using a Varian 720-ES Inductively Coupled Plasma Optical Emission Spectrophotometer fitted with an SPS-3 autosampler and ultrasonic nebuliser. Water samples for pH and EC were kept frozen until needed, upon which they were thawed and directly analysed on the equipment described below. Soil pH was measured in a soil:water extract (1:2.5) after a 20–24 h stabilisation period post water addition (Blakemore et al., 1987). Soil EC was measured in a soil:water extract (1:5) with a Mettler Toledo SevenEasy pH/EC Meter equipped with a Mettler-Toledo Inlab®730 conductivity probe calibrated to a 1412 μS/cm standard. A Mettler Toledo SevenEasy pH/EC Meter equipped with a Mettler Toledo Inlab®413 electrode was used to measure soil pH and EC. Organic C was analysed on the Elementar Vario-Max CN Elemental Analyser by the 'Solid-TOC for elemental analyser vario MAX' method (Elementar, 2013). Total N was analysed by an Alpkem FS3000 twin channel analyser following Kjeldahl digest of soil material. Post-digestion the samples were filtered (Whatman 52, hardened) before the analysis. Intact soil cores (5 cm diameter by 7.5 cm height) were taken at a rate of one per organic matter transect, dried at 100 °C for 24 h, and then weighed so that bulk density could be calculated.

2.4. Statistical analysis

Organic C and N data were analysed statistically in two ways, firstly treating all samples as spatially uncorrelated and using analysis of variance (ANOVA), and secondly using geostatistical techniques

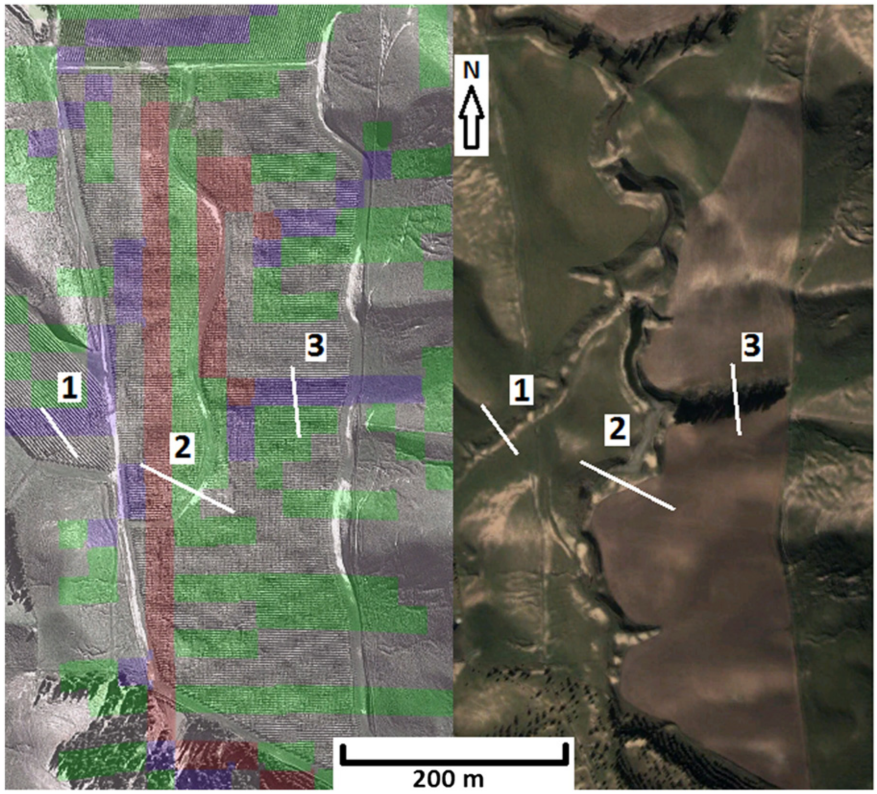

Fig. 4. Post-recontouring landscape with superimposed ArcGIS 'stream order' function (left), and pre-recontouring aerial photo highlighting gullies (right). The white lines labelled 1, 2, and 3 represent the drainage transects completed. The stream orders increase in predicted flow from green to purple to red. Image © DigitalGlobe 2013, from © Google Earth, 2013.

(semivariance and semivariograms) to explore spatial autocorrelation. One-way ANOVA were carried out on organic C and N (as dependant variables) separately, for which sample site disturbance (virgin/recontoured) was the independent variable. This was carried out in the statistical software package R (version 3.0.1). A series of four variograms were constructed in R (version 3.0.1) to examine the variability structure of the organic C and N data on both virgin and recontoured sites. This utilised the 'gstat' package for R (Pebesma, 2004). Data utilised for this analysis included XY coordinates in the New Zealand Transverse Mercator (NZTM) projection system and organic C and N values in units of mg organic C/N per profile.

Statistical analysis of the drainage transect data included ANOVA and Tukey's Honestly Significant Difference tests carried out in the R statistical package (version 3.0.1).

3. Results and discussion

3.1. Soil morphology and chemistry

An example of the undisturbed soil on this property was exposed on an upper slope section proximal to but not in the vineyard (Fig. 5 for location, Table 2 for description). This soil (designated HCV-US), which is currently under pasture, exhibited a gradual texture change between the Silt Loam (SiL)/Clay Loam (CL) of the upper 25 cm of soil to the sticky and plastic clay of the lower 120 cm of profile. This transition occurred between the Bw and Bt horizons, the latter of which displayed some faint mottling, suggesting slight seasonal waterlogging at the top of the Argillic horizon. Plant rooting was not disturbed by this texture contrast and continued to the base of the profile. Strongly developed sub-angular blocky structure was present in both the Bt and C horizons, whereas the Ah and Bw horizons possessed that same type of structure but of only a moderate grade. The apparent strong structure described in the C horizon may be a relict of desiccation cracking or structure formed into the marine siltstone during the formation of the stone. Clasts were not present in this soil, or any of the following described soils.

In contrast to this profile, the recontoured upper slope soil (in grass sward between vine rows) exposed in pit HCR-US (Mixed Anthropic soil, Hewitt (2010)) showed a lack of natural soil horizonisation, instead showing a simple profile consisting of a mixed A horizon and a mixed B

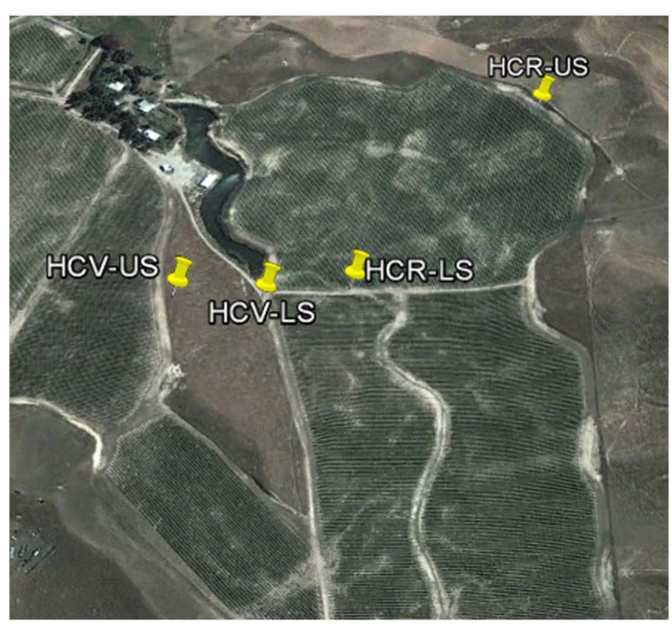

Fig. 5. Hardcase pit locations. Image © DigitalGlobe 2013, from © Google Earth, 2013.

Table 1
Soil profile morphology data for lower slope soil pits on Hardcase property.

Horizon	Colour	Mottles	Texture	Clasts	Consistence	Structure	Cutans	Roots	
Lower virgin slope soil pit (HCV-LS) 41°42′39.48″S 174° 6′53.28″E NZSC: Sodic Argillic Pallic soil USDA soil tax.: typic Natrustalf									
Ah 0–17 cm, clear smooth boundary	10 YR 4/2	–	Silt loam	–	Slightly hard, slightly sticky, plastic	Moderate, medium, blocky	–	Common, very fine	
Bt1 17–34 cm, gradual smooth boundary	2.5 YR 6/4	–	Clay	–	Slightly hard, very sticky, plastic	Moderate, medium/coarse, blocky	–	Few, very fine	
Bt2 34-105 + cm	10 YR 6/4	Few, fine, distinct, 10 YR 5/6	Clay	–	Very hard, very sticky, very plastic	Strong, moderate/coarse, blocky	3 p pf 10 YR 5/3 cutans	Few, very fine	
Lower recontoured slope soil pit (HCR-LS) 41°42′38.88″S 174° 6′56.82″E NZSC-mixed anthropic soil USDA soil tax.: typic Ustorthent									
Ap mixed 0–28 cm, cl sm	10 YR 3/2, 10 YR 5/8 (subsoil), 10 YR 2/2	–	Clay loam	–	Friable, sticky, plastic	Moderate, medium, blocky	–	Many, very fine	
B mixed 28–120 +	2.5 YR 5/4, 10 YR 2/2, 5 YR 5/2 (siltstone)	–	Clay	–	Friable, very sticky, very plastic	Massive	–	Few, very fine	

Key for morphology: Horizon (distinctness/shape); Mottles (quantity/size/contrast); Texture; Consistency (dry or moist/stickiness/plasticity); Structure (grade/size/type); Cutans (amount/distinctness/location); Roots (abundance/size).
Key for classification: NZSC — New Zealand Soil Classification (Hewitt, 2010), USDA Soil Tax. — United States Department of Agriculture *Soil Taxonomy* (Soil Survey Staff, 2010).

horizon (Table 2). The soil colours reflected a mixing of subsoil and siltstone into the A horizon, and similarly topsoil and siltstone occlusions were present within a matrix of B horizon. These horizons changed from a moderately developed sub-angular blocky structure with a clay loam texture in the topsoil to a massive clay subsoil. This profile trend of structure contrasts with the HCV-US soil, which possessed strong structure grade. The soil chemistry depth trends of this soil relative to HCV-US showed less variation in total exchangeable bases over the profile, higher pH, and no increase in EC and exchangeable Na with soil depth (Table 3). These differences highlight the reduction of horizon definition and profile differentiation in disturbed soils. (See Tables 4–6.)

Lower on the slope to where HCV-US was exposed, the pit HCV-LS (Sodic Argillic Pallic soil) was opened as another control soil under pasture (Fig. 5 for location, Table 1 for description). This soil had similar morphology to the HCV-US soil, except that the textural contrast between the SiL topsoil and clay rich Argillic (Bt1, Bt2) horizons was sharp and did not transition through a CL-textured layer. The clay illuviation evident in the HCV-LS was strongly expressed, as shown by many prominent clay skins on ped faces in the Bt2 horizon. Both Bt1 and Bt2 horizons were found to be very sticky and very plastic with subangular blocky structure, ranging from moderate (Bt1) to strong (Bt2) grade. Roots penetrated to the base of the profile, although in the Bt2 horizon the roots were few and very fine.

The second pit opened to expose a soil representative of the recontoured part of the vineyard was located under grass sward between vines (Fig. 5). This soil (HCR-LS, Mixed Anthropic) showed highly mixed soil horizons, which were designated mixed A and mixed B horizons (Table 1). Like the HCR-US soil these horizons showed the occlusions of allocthonous material that had been integrated in the recontouring process; for example subsoil and siltstone occlusions were found in the topsoil. The topsoil was a CL with moderate subangular blocky structure, whilst the subsoil was a massive very sticky and very plastic C horizon. Soil chemistry trends in the disturbed lower slope soil compared to its virgin counterpart showed increases in pH and EC over the profile, and higher TEB and exchangeable Na in the upper 50 cm of the profile (Table 3).

Changes to soil morphology from recontouring on the Hardcase vineyard showed a shift towards a simple soil profile form that lacked horizon differentiation relative to the undisturbed soils. Virgin soils were classified under the New Zealand Soil Classification (Hewitt, 2010) as an Sodic Argillic Pallic soil on the basis of Sodic features (ESP >6%, Table 3), Argillic features (argillic horizons, continuous clay coatings), and Pallic soil features including moderate/high base status (Table 3), pale colour, and high subsoil bulk density (data not shown). The resultant recontoured soils were classified as Mixed Anthropic soils and had relatively simple profile forms; typically Ap/mixed-B/C. Recontouring has reduced contrasts within the soil, but potentially increased contrast between the solum (A and B horizons) and the R horizon. The greatest difference in soil morphology, aside from profile form, was a decrease in subsoil structure grade from moderate/strong in the virgin soils to massive structureless in reconstructed soils.

Table 2
Soil profile morphology data for upper slope soil pits on Hardcase property.

Horizon	Colour	Mottles	Texture	Clasts	Consistence	Structure	Cutans	Roots	
Upper virgin slope soil pit (HCV-US) 41°42′39.84″S 174° 6′49.86″E NZSC: Sodic Argillic Pallic soil USDA soil tax.: typic Haplustalf									
Ah 0–15 cm, cl, sm	10 YR 4/2	–	Silt loam	–	Friable, non sticky, plastic	Moderate, fine/medium, blocky to moderate, fine, granular	–	Few, very fine	
Bw 15–25, gr sm	10 YR 5/4	–	Clay loam	–	Very friable, non sticky, plastic	Moderate, medium, blocky	–	Very few, very fine	
Bt 25–90, gr sm	10 YR 5/6	Few, fine, faint, 7.5 YR 4/6	Clay	–	Firm, sticky, plastic	Strong, medium/coarse blocky	Few, faint, ped face 10 YR 5/3	Few, very fine	
C 90–145 +	2.5 YR 5/3, 5 YR 5/2 (siltstone)	–	Clay	–	Firm, very sticky, very plastic	Strong, fine/coarse, blocky	–	Very few, very fine	
Upper recontoured slope soil pit (HCR-US) 41°42′30.90″S 174° 7′5.34″E NZSC: mixed anthropic USDA soil tax.: typic Ustorthent									
Ap mixed 0–40 cm, cl sm	10 YR 4/2, 2.5 YR 5/4 (subsoil), 5 YR 5/3 (siltstone)	–	Clay loam	–	Friable, sticky, plastic	Moderate, medium, blocky	–	Common, very fine/fine	
B mixed 40–105 +	2.5 YR 5/4, 10 YR 4/2 (topsoil), 5 YR 5/3 (siltstone)	–	Clay	–	Friable, very sticky, very plastic	Massive	–	Few, fine	

Key for morphology: Horizon (distinctness/shape); Mottles (quantity/size/contrast); Texture; Consistency (dry or moist/stickiness/plasticity); Structure (grade/size/type); Cutans (amount/distinctness/location); Roots (abundance/size).
Key for classification: NZSC — New Zealand Soil Classification (Hewitt, 2010), USDA Soil Tax. — United States Department of Agriculture *Soil Taxonomy* (Soil Survey Staff, 2010).

Table 3
Soil chemical properties.

Horizon	pH (H_2O)	EC (μS/cm)	ESP	Ca (meq/100 g soil)	K	Mg	Na	TEB
HCV-US								
Ah	5.4	75	2	6.2	1.7	1.7	0.2	9.8
Bw	5.9	51	2	5.9	0.2	2.1	0.2	8.3
Bt (25–55 cm)	6.8	83	7	11.5	0.1	5.3	1.2	18.1
Bt (55–85 cm)	7.3	201	13	13.5	0.4	7	3.2	24
C	7.2	467	18	11.4	0.6	7	4.2	23.1
HCR-US								
Ap mixed	6.2	64	2	9.4	0.8	3	0.4	13.6
B mixed (35–55 cm)	7.8	110	3	16.9	0.6	4.4	0.4	22.3
B mixed (55–75 cm)	7.2	57	4	11.8	0.6	5.2	0.7	18.3
B mixed (75–95 cm)	8.2	184	6	12.9	1.5	4.5	1.2	20.2
HCV-LS								
Ah	6.2	75	6	7.5	0.4	3.8	0.8	12.5
Bt1	6.4	83	8	7.4	0.1	4.5	1.1	13
Bt2 (35–55 cm)	6.9	102	13	8.4	0.4	5	2	15.8
Bt2 (55–75 cm)	6.9	779	23	11.4	0.3	7.5	6.2	27.3
Bt2 (75–95 cm)	6.7	833	29	7.7	0.3	5.5	5.4	18.9
HCR-LS								
Ap mixed	7.0	222	8	10.4	0.6	3.1	1.2	15.2
B mixed (30–50 cm)	8.2	299	8	12.1	0.8	4.3	1.5	18.8
B mixed (50–70 cm)	8.6	347	13	16.9	0.7	6.1	3.7	27.4
B mixed (70–90 cm)	8.1	674	15	13.5	0.3	3.6	3.1	20.4
B mixed (90–110 cm)	7.9	960	16	16.6	0.4	4.6	4.1	25.7

3.2. Soil carbon and nitrogen

Within the virgin landscape, the analysis of variance showed significant differences ($P < 0.05$) in both C and N amongst the different slope units. Topsoil mass of both C and N was significantly ($P < 0.05$) higher in the footslope than in the midslope or summit. The latter two slope positions had non-significant differences.

Sample semivariograms derived from the virgin transect data showed spatial structure for both C and N variability (Fig. 6a and b). The range of both semivariograms and hence the limit of spatial autocorrelation were about 50 m, the limit of which corresponds to the characteristic dimension of the slope elements. The sills of the semivariograms were 170,000 mg^2 and 1250 mg^2 for C and N, which vary proportionately with the respective sample variances for the two soil properties of 120,926 mg^2 and 896 mg^2. The null hypothesis of data homoscedasticity for both C and N could not be rejected due to Levene's test values above $P < 0.05$.

Table 4
Mean organic C and N values on different virgin slope elements ($n = 30$).

	mg C/soil profile	C std dev	mg N/soil profile	N std dev
Footslope	1116	382	100	33
Midslope	732	358	66	33
Summit	579	223	44.4	12

Table 5
Mean organic C and N values on Recontoured/Virgin sites (n = 60).

	mg C/soil profile	C std dev	mg N/soil profile	N Std dev
Recontoured	683	270	75	25
Virgin	855	403	59	36

Table 6
Average EC and pH for the three drainage transects (n = 44).

	EC (μS/cm)	EC Std dev	pH (H_2O)	pH Std dev
Gully	719	565	6.7	0.6
Non-gully	228	160	6.2	0.9

The transects on the recontoured land were not stratified in any way owing to the homogeneity of the topography. The analysis of variance between the recontoured and virgin parts areas showed no significant difference between soil profile masses of C, but a significant difference ($P < 0.05$) for N. The r-square value for the ANOVA for N showed, however, that the treatment effect (recontoured vs virgin) accounted for less that 5% of the variance, leaving the remaining 95% accounted for by other effects such as topographic effects on soil N profile mass. Sample semivariograms from the transects showed pure nugget effect for both C and N, implying that any structure to the spatial variation in N and C on recontoured land occurs over distances less than the minimum sample separation (20 m). The sills for the semivariograms, which are equivalent to the nugget variances, were 76,000 mg^2 and 720 mg^2 for C and N, respectively. These compare to the variance that they approximate of 73,041 mg^2 and 648 mg^2, respectively. The overall effect of recontouring on profile C and N contents is one of the homogenisations without significant loss of either soil component.

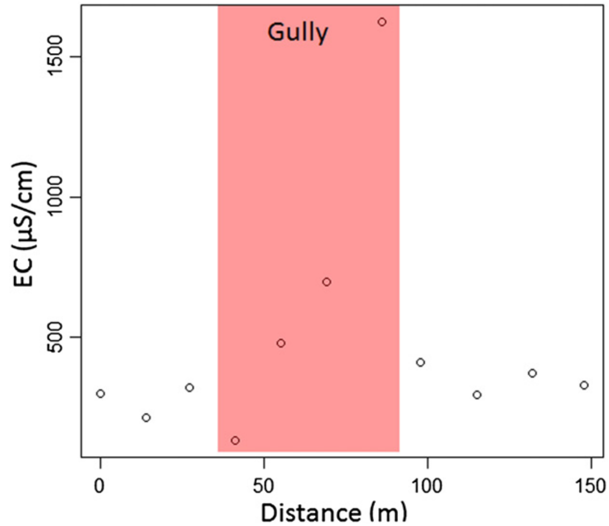

Fig. 7. Profile of EC across drainage Transect 2 (Fig. 4). Direction left to right in this figure equates to west to east in the above figure. Each point is an average of the three sample depth increments (20 cm, 40 cm, and 70 cm) taken from each auger.

The hypothesis that recontouring would reduce topsoil organic C and N was rejected on the strength of a lack of significant difference between virgin and recontoured soil organic C, and a low R-squared value (0.04) for the $P < 0.05$ significant difference for organic N. This result confirms that it is possible, with appropriate recontouring practices, to

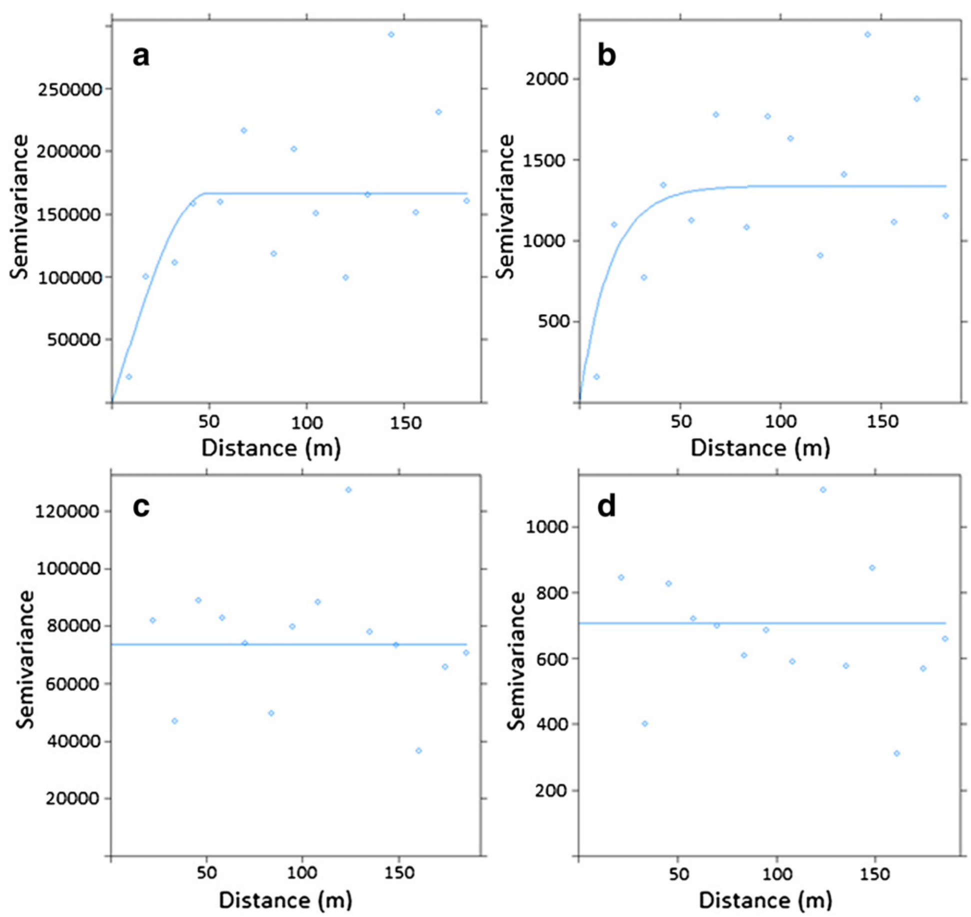

Fig. 6. a, b, c, d. Semivariograms of virgin landscape organic C and N (6a and 6b) and recontoured landscape organic C and N (6c and d).

carry out recontouring and not cause a decrease in topsoil organic matter. Contributing factors for this result may include the care taken by site owners to keep topsoil in piles for the minimum amount of time possible and to re-spread it to generally even thicknesses. In contrast, recontouring had a significant effect on the spatial variability of C and N. Virgin soils showed significant differences (at 95% confidence) in organic C and N between slope positions (summit-footslope, midslope-footslope), with the highest to lowest values in the order footslope to midslope to summit. Robertson et al. (1993) also found an altered variability structure in soil properties (gravimetric water, inorganic P, total C) of disturbed land as compared to virgin land, although the cited study disturbance was due to cultivation (Robertson et al., 1993). The range over which spatial dependence of soil properties was expressed in the study by Robertson et al. (1993) was greater in the cultivated soil (48–108 m) than in the undisturbed soil (7–26 m). This pattern is the opposite to what was observed in Hardcase vineyard topsoil organic C and N data, and may reflect the large weighting of disturbance type on its resulting effect on spatial dependence. The combination of topsoil homogenisation and no significant loss in topsoil organic C and N resulting from recontouring may be a desirable effect for the vineyard. Soil variability in Marlborough has been shown to be a driver of intra-vineyard crop variability, and hence resultant juice quality (Bramley et al., 2011; Trought and Bramley, 2011). With soil variability on Hardcase having been reduced by topsoil homogenisation, it could be expected that blocks of vines will ripen more uniformly than if vines had been planted in the more variable virgin soil.

3.3. Soil salinity

Statistical analysis of EC and pH data of ‘Gully’ versus ‘Non-gully’ soil auger samples showed a significant difference in EC ($P < 0.001$), and no difference in pH. Depth trends of EC at different soil auger depths (20–30 cm, 40–50 cm, and 70–80 cm) showed the highest EC at 20 cm in the main gully fill (Transect 2, Fig. 4), whereas across the infilled tributary gully (Transect 1) EC reached its highest value at 70 cm depth (depth data not shown). The high EC values were not accompanied by an increase in pH as would have occurred if the increase in salinity was due to an abundance of siltstone clasts in the fill material. Instead

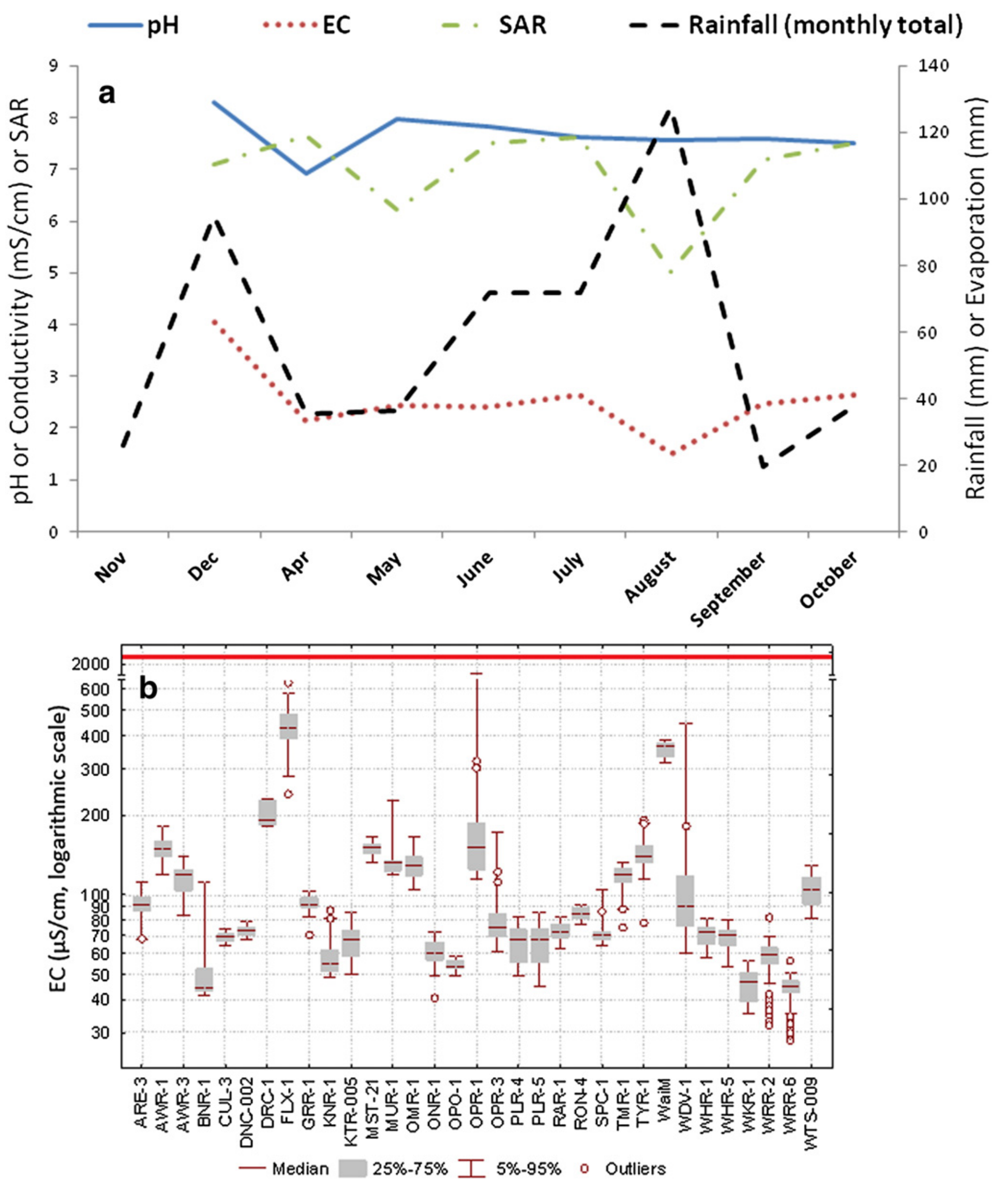

Fig. 8. a. Pond water time series data for November 2011 to October 2012. Note the data gap between December and April; 8b. Marlborough region water EC data from 34 waterways. The red line indicates the Hardcase pond water average for the 9 months it was measured.

it appears that the increase in EC is due to the concentration of salts in the gully fill by leaching and throughflow. The higher concentration of salts towards the surface of the large gully relative to the smaller gully reflects differences in their contributing areas, and the frequency and magnitude of saturation events. In winter 2010 a seep formed along the length of the large gully, which brought salts that formed a surface efflorescence and killed grapevines (Pers. Comm. P. Clark, 2013). Fig. 7 shows the EC profile of the auger transect that traverses the main infilled gully (Transect 2 in Fig. 4). There is an abrupt increase in EC in the 'Gully' area, dominantly in the final auger hole of the 'Gully' zone.

Recontouring effects on site hydrology are also interesting as the relief in the underlying bedrock on Hardcase has been reduced in the process; a review of a group of studies in New Zealand on hillslope hydrology noted that bedrock topography appeared to determine spatially the pathway of rapid saturated subsurface water flow and tracer breakthrough at a hillslope scale (McGlynn et al., 2002). This suggests that former gullies (now infilled) will still receive subsurface water flows as directed by upstream surface and bedrock topography in unmodified areas, but that lateral throughflow may be diffuse. Vine growth and viticultural production are likely to be adversely affected at the high end of these EC values (Paranychianakis and Chartzoulakis, 2005). Alterations to finished wine pH and colour in wine made from grapes grown in high salinity soil may be seen as a potential positive outcome (Walker et al., 2000).

3.4. Pond water

The pond collecting the drainage from the vineyard had a year-round moderate-high pH (average 7.7) and high EC (average 2.5 mS/cm, Fig. 8a). Water EC appeared to respond to rainfall; after high rainfall months the salt content was diluted (e.g. August). The pH fluctuated less with changing rainfall and evaporation values. The Sodium Adsorption Ratio (SAR) is an indicator of the amount of sodium relative to calcium and magnesium; higher values indicate higher amounts of sodium and increased risk of reduced infiltration due to clay dispersion (Grattan, 1999). The SAR responded similarly to EC, decreasing when rainfall increased.

Comparison of the EC values from this pond with those of 34 reference waterways, including areas of similar geology, around the Marlborough region (Fig. 8b) shows recontouring not only is resulting in remobilisation of salts into gully fills, but also salts are accumulating in the irrigation pond to levels much greater than those present in natural waterways in the region.

4. Conclusion

Landscape recontouring has had a variety of effects on soils and near-surface hydrology on a hilly vineyard site in the Awatere Valley. Recontoured soils have shown a shift towards more simple profile forms. The morphological differences have led to the recontoured soils being classified as Mixed Anthropic Soils comprising a sequence of restored A horizon material over mixed, reconstituted B + C horizon material, in place of the A/Bt/B(x) horizon sequence characteristic of the Sodic Argillic Pallic soils found in the undisturbed landscape. Reconstructed soils lacked the strong structure of the virgin soils, which together with high exchangeable Na may predispose them to dispersion, compaction, and possibly enhanced erosion. Potential methods of enhancing soil structure restoration and alleviating high exchangeable Na include the application of gypsum and encouraging plant growth. Recontouring resulted in no significant difference in profile mass of organic C when compared to virgin soils, but spatial variability was reduced in magnitude. These results suggest recontoured land may produce grapes of more uniform characteristics and hence quality.

Infilled gullies remain the zones of water transport although as throughflow rather than channelised flow. Solutes, and in particular salts, have been mobilised in diffuse throughflow and concentrated in the centre of infilled gullies, creating zones of high EC, and in some areas, zones of seeps of saline water. The source of the salts is siltstone bedrock incorporated into gully fills and surrounding reconstructed soils. An irrigation pond designed to collect drainage from the landscape now has salinity levels above that recommended for irrigation. This issue may potentially be alleviated by draining the irrigation pond and letting it refill with fresh rainwater, but it is likely that more salts will accumulate as a result of rainwater throughflow in the surrounding landscape.

A follow up study in 5–10 years time could prove useful in understanding the long term effects of recontouring on the soil resource in the Awatere Valley sub region in Marlborough, New Zealand.

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