MAPPING OF SOILS IN SINGLETON TRAINING AREA BY REFERENCE TO AIRBORNE MEASURES OF GAMMA-RADIATION

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ABSTRACT

This study was undertaken to provide a means of mapping soil categories relevant to management independently of other information used in landscape analysis, such as geology and vegetation. To this end, airborne radiometric data were examined as an alternate to geological formations in stratifying the landscape to map soils.

Reconnaissance grade airborne radiometric data at 1.6 km spacing between flight lines, 60 m intervals along flight lines and 150 m elevation were grided at 100 m resolution using the spline algorithm to produce a 4 channel image of total count, potassium, uranium and thorium. The resulting image was classified using measures of spectral similarity and spatial adjacency to produce a map of 16 radiometric classes.

Three transects were located within each uniform radiometric area (patch) with soil properties being measured for boreholes at positions of lower slope, mid slope and crest. The properties pH, field texture and Munsell colour were measured for the A1, A2 and B2 soil horizons, and profile thickness for the A1 and A2. Soil texture and colour categories were converted to pseudo-continuous variables for statistical analysis. Resutls were analysed using generalised linear modelling to determine relationships between soil properties and catenary position and radiometric patterns.

Significant effects associated with radiometric patterns were obtained for the measured variables of textures of the A1, A2 and B, thickness of the A and A1, pH of the A2 and B and colour of the A1, A2 and B. Significant effects for the derived variables were the ratio of textures for the B and A2, the ratio of the pH for the B and A1 and the ratios of colour for the A1, A2 and B. Catenary effects were only significant for the thickness of the A and A1 horizons.

Radiometric patches were aggregated according to the statistical significance of differences in soil properties to produce a soils map, with map classes labelled according to the measured soil properties. The results demonstrate the applicability of the airborne radiometrics in mapping soils, and are discussed in relation to their applicability in management.

INTRODUCTION

Results for the previous phases of the soil survey of the Singleton Training Area (STA) attributed major differences in spatial patterns soil properties to geology, with much smaller differences being associated with catenary position (Tunstall and Gourlay, a). Eighteen classes of soil in the STA were statistically identified through the analysis of soil properties, and were mapped by reference to geological formations and a classification of topography. This prior study, which represents a detailed implementation of the soil landscape mapping approach, was significant in demonstrating statistical significance for the derived soil categories, but it contained limitations.

A second study on STA (Gourlay and Tunstall) identified the existence of spatial patterns in soils not categorised by the initial soil map: the landscape mapping approach did not identify all significant patterns in soils. Moreover, the detailed landscape mapping approach has practical limitations as implementation depends on the availability of detailed geological information not normally available, and the mapped results are dependent of data that would normally be used for analysis of spatial relationships in GIS (elevation). Lack of independent derivation of layers restricts subsequent analysis in GIS, particularly where the identification of causual relationships is required.

The objective of this study was to provide a means of mapping soil information relevant to management independently of other information generally used in environmental analysis, such as vegetation, geology and topography. The map base investigated was airborne measures of gamma-radiation (radiometrics) as the radiometric signal depends mainly on the parent material and degree of weathering of the surface material. As soils derive from the weathering of parent material, the radiometric data should identify spatial patterns of variation in soils. Other studies showed radiometric properties to be generally related broad soils information (Tunstall and Marks, a., Bierwirth, 1994)

The Radiometric Data

Airborne radiometric data are obtained at around 60m intervals along flight lines spaced between 100 and 1,500m apart. The aircraft height above the ground is minimised to limit atmospheric attenuation of the signal, and generally ranges between 60 and 150m depending on the flight line spacing. The data are processed to adjust for atmospheric attenuation, and are gridded to form a cohesive image. The measurements are generally partitioned into energy levels indicative of potassium, uranium and thorium which, together with total count, provides a four band image.

The radiometric image can be analysed similarly to a digital satellite image, but significant differences exist between the forms of data. Airborne radiometric data invariably contain spurious effects due to variations aircraft height, atmospheric attenuation, and variations in soil moisture. Some effects can minimised in the initial processing, as with relating results to a constant height above the ground, and adjusting the energy windows (bands) according to atmospheric conditions. However, atenuation of the signal due to soil moisture cannot be adjusted for, and the non-point nature of the measurement limits the levels of resolution and adjustment possible. The radiometric measurement does not provide a uniform spatial average, as does a satellite image pixel, and there is overlap between areas contributing to individual measurements. These spatial characteristics of the signal limit the correlation achieveable between ground and airborne radiometric measures, and can produce uncertainty in the location of boundaries associated with features.

Application of airborne radiometric data for mineral exploration can be limited by the confounding between effects of parent material and weathering, and the derivation of the signal from around the top 30 cm of soil. However, soils are essentially determined by parent material and weathering, hence this aspect of radiometric data should not be limiting for the purposes of mapping soils. The surficial nature of the measurement may sometimes be limiting, as where the surface is covered with shallow wind blown deposits, but surface soil properties are generally either related to, or are afected by, the underlying material (Tunstall and Gourlay, a). The radiometric signal therefore usually reflects the soil profile and not just the soil surface.

It was assumed for this study that soil types or properties are unlikely to be uniquely related to the characteristics of the radiometric signal because of the number of factors affecting the signal: equivalent signals can arise for different reasons. (A similar situation arises when using topography and geology to map the distribution of soils as there is no unique association between soil properties and geology or topography, either alone or in combination.) However, radiometric data can be used to define spatial patterns by way of uniform areas, disjuncts or boundaries, and gradients. Therefore, radiometric mappings may provide a reliable basis for field sampling of soils information, data analysis and extrapolation / interpolation of results for land management purposes.

METHODS

Radiometric Analysis

The study area, and the survey and sampling methods used in the initial survey and applied in this phase of the study are described by Tunstall and Gourlay (a).

Reconnaissance grade airborne radiometric data were provided by the New South Wales Department of Mineral Resources. These data were acquired in 1984 at 1.6 km spacing between flight lines, 60 m intervals along flight lines, and 150 m height above the ground. The raw data for a 18 x 20 km area covering STA were corrected by Geoterrex Pty Ltd and grided at 100 m resolution using the spline algorithm of Hutchinson (1989) to produce a 4 channel image of total count, potassium, uranium and thorium. For such data, around 90% of the measured signal derives from an ellipse of length around 850m along the flight line and extending 400 m either side of the flight line.

The 12 flight lines covering STA represent a minimal data set given the spatial and spectral resolution of such data, and the 100 m grid represents an ambitious interpolation. The griding was therefore repeated a number of times to seek an optimum condition of a cohesive image showing high spatial definition. An optimum solution could not be achieved for total count where flight lines remained obvious even with heavy smoothing. The fine variance about flight lines was therefore ignored and the images for all four bands were obtained using minimum smoothing.

The grided data were further corrected using the procedure of Green (1987), with the modification of deriving the variance used in the correction from the band to be corrected. This modification, represented by the RC_ANOVA program in the microBRIAN image analysis system, applies a statistical smoothing to all four bands which reduces banding associated with differences in instrument response between flight lines.

The patterns in the radiometric classification matched the general geological patterns when locally adjusted, but appeared offset when referenced using the spatial positioning provided with the radiometric data. The radiometric image was therefore shifted by 1000m to the north and 500 m to the west to align with the geology map. This repositioned image was used for subsequent mappings, and when locating field sampling sites.

The composite four channel radiometric image of total count, potassium, uranium and thorium was classified using a minimum distance algorithm, and measures of spectral similarity and spatial adjacency. Initially, a large number of classes was generated automatically but in an iterative fashion. Iteration was achieved by commencing with broad limits for the distribution of values about the mean and then progressively reducing these limits. The number of classes was then iteratively reduced by combining or aggregating classes that were spectrally similar and spatially linked. This use of spatial as well as spectral information in the image maximises the resolution, which is necessary with such low resolution data. This procedure also facilitates the identification of natural boundaries.

Spatial adjacency was determined using a co-occurrence analysis (Tunstall et al. 1984). This analysis has the theoretical limitation that the first significant result negates further comparisons. This limitation is of little consequence in heterogeneous images but is significant in homogeneous images where the classes form large patches. The within class comparisons then mask and distort the results for comparisons between classes. This limitation was circumvented by deriving the measure of spatial association using pixels located on the boundaries between classes. The mask of non-boundary pixels was obtained by identifying variance using a 3 x 3 filter, where the variance for non-boundary pixels in a classified image is zero..

The final aggregation provided an image with 17 radiometric classes, one of which did not occur within STA. This number of classes was not predetermined but reflected the results provided by the statistical analyses within the practical constraint that for comprehension and mapping the final number of classes should generally lie between 10 and 30.

The classes in the soils map were based on field descriptions of the soil properties within the radiometric patches. Some radiometric classes were amalgamated while some spatially separate patches of classes were assigned separate labels. The final image (soils map) was smoothed using averaging filters to remove any artificial appearance of spatial precision.

Table 1. Replication for sampling by catenary position and radiometric patch.

	Radiometric Patch	1	2	3	4	5	6	7	8	9	10	11	12	13	14	16	17
	Catena	Number of Observations															
7	Levee	3	1		1		1			1	4	1					
9	Lower Slope	3	4	2	5	4	3	3	3	3	6	3		2	6		2
10	Mid Slope	4	5	2	5	4	3	3	2	3	5	3	1	2	4	2	2
11	Upper Slope	3	1		1	2			2	1	4	1			2		
12	Crest	3	4	2	5	5	3	2	2	3	6	2	1	2	5	2	2

Soil Analysis

Each mapped area of significant size (radiometric patch) was regarded as being unique for the purpose of field sampling. The sampling strategy was to obtain 3 transects within each patch, but not all of the 18 classes were sampled because of access limitations.

Soil descriptions from the prior soil surveys were utilised where possible, and no additional sampling was required for 3 patches. In the initial phase of this study, three transects were located within each of 6 geological formations with boreholes located at 5 catenary positions along each transect. In the second phase of the study, further observations were obtained within the oldest geological formation in STA for the catenary positions of lower slope, mid slope and crest. Field observations were used to confirm the location of prior transects within patches because of the uncertainties associated with the spatial referencing of the radiometric data. This confirmation involved identification of the boundaries between patches. Prior data were not used where transects traversed boundaries between patches.

An additional 64 boreholes were sampled for this study with measurements along transects at the catenary positions of lower slope, mid slope and crest. The replication for each class is given in Table 1.

The soil characteristics measured for the A1, A2 and B2 soil horizons were pH, field texture and Munsell colour. The thickness of the profile was also measured for the A1 and A2 horizons. All variables were measured using the techniques described by Northcote (1979). However, colour was not recorded during the second phase.

The combined soil data were analysed using generalised linear modelling with patches being treated as a factor and catenary position as a variable. Texture was analysed as a continuous variable as indicated in Table 2.

Table 2 Number codes and the logic used in the derivation of descriptions for soil texture, pH and colour and depth.

Soil Texture

#	qualifier	
1	coarse	**Gravel**
2	medium	
3	fine	
4	coarse	**Sand**
5	fine	
6	loamy	
7	clayey	
8		**Sandy Loam**
9	fine	
10	clay	
11	fine sandy	**Loam**
12		
13	silty	
14	sandy	**Clay Loam**
15	silty	
16		
17	sandy	**Clay**
18	silty	
18	light	
20	medium	
21	heavy	

Texture Grade

< 2	Uniform
2 - 3.9	Gradational
=> 4	Duplex

pH

< 4.6	Highly Acid
4.6 - 5.5	Acid
5.6 - 6.5	Slightly Acid
6.6 - 6.9	Neutral -
7.0	Neutral
7.1 -7.4	Neutral +
7.5 - 8.4	Alkaline
=> 8.5	Strongly Alk.

Depth of A

0 - 4	Superficial
5 - 9	Shallow
10 - 19	Thin
20 - 29	Intermediate
30 - 50	Thick

Colour

<4	Dark
4 - 4.9	Coloured
5 - 5.9	Pale
=> 6	Bleached

RESULTS

The radiometric classification and mapping of the patches used for soil sampling is given in Fig 1. The open numbers refer to radiometric classes. The encircled numbers refer to the patch numbers used for sampling and analysis. Generally, each radiometric class was effectively represented by only one patch but, in the main area of interest, one class was represented by 3 patches and another two by 2 patches. The patches were large as evidenced by the occurrence of only 26 significant patches in STA.

Boundaries between the mapped radiometric classes were verified during field sampling. Most boundaries were clearly evident through changes in soil colour, parent material and vegetation. The error in the positioning of the boundaries on the map was generally within 250 m, with a minimum error of 100 m and a maximum error of 500 m. Errors were generally lowest in the northern portion of STA, which has the lowest relief.

The position of the boundaries in the landscape varied considerably, but most could be readily identified. One boundary cut across the centre of an airfield (very flat terrain), while another was located on a creek line and represented the edge of an alluvial flat. The boundary of one patch could be readily identified even though the patch boundary was not related to topography. The general area was mainly grassland but the boundary was evidenced by a change in grass species and the occurrence and abundance of weed species. The radiometric mappings confirmed differences that had previously been observed between transects within geological formations but additionally identified many others.

The radiometric mappings located soil boundaries that had not been identified by other survey methods but did not identify all boundaries that would normally be regarded as significant for management. This is evidenced by differences between the geology map (Beckett, 1988) and the radiometric classification. Moreover, some soil boundaries were observed that are not identified in either map. For example, neither map differentiated an area of deep uniform sand overlaying sandstone from an adjacent area of similar material, but with shallower and more compacted soils containing significant amounts of rounded gravel.

Associations between soil properties where the correlation coefficient is 4 or higher are given in Table 3. Comparisons involving non-independence, as can arise with derived variables, have not been included. The most significant correlations are between the textures and thicknesses of the different soil layers, excepting the A1. Additionally, the pH of the B horizon is correlated with the textures of all horizons and the ratio of the pH of the B and A1 horizons is correlated with the texture of the B horizon.

Table 3 Correlation coefficients (r) for comparisons between soil properties for r of 0.4 or above.

	Th A2	**Th A**	**Tex A1**	**Tex A2**	**Tex B**
Tex A1	-0.42	0.40			
Tex A2	-0.48	-0.44	0.94		
Tex B	0.60	0.55	0.67	0.69	
pH B			0.45	0.40	0.44
pH B1 - A1					0.40

The only significant effects associated with catenary position relate to the thickness of the A horizon (Table 4). The thickness of the A1 and total thickness of the A are related to catenary position, but the thickness of the A2 is not. The significance of effects associated with patches are also given in Table 4. This illustrates that effects associated with patches for the thickness of the A1 and A2 are reversed compared with catenary effects, while those for the total thickness of the A horizon are similar.

Table 4 Means and least significant differences for effects of catenary position on the depths of the A horizons (cm). The variance ratio is also given for patches for comparison.

	Variance Ratio		**Means for Catenary Position**					**LSD**
	Patch	**Catena**	**Levee**	**Lower Slope**	**Mid-Slope**	**Upper Slope**	**Crest**	**Catena**
Th A1	2.5	11.0	8.7	3.8	3.3	3.1	2.8	4.2
Th A2	7.0	3.0	20.2	16.3	12.8	11.9	13.4	9.1
Th A	6.8	6.5	28.9	20.1	16.1	15.0	16.2	12.8

The analysis indicates few significant effects associated with catenary position, and no significant interactions between patches and catenary position. In consequence, the tabulation of means for each patch (Table 5) shows most of the significant effects. This table demonstrates significant effects for the measured variables of textures of the A1, A2 and B, thickness of the A and A1, pH of the A2 and B and colour of the A1, A2 and B..

Derived variables showing significant effects attributable to patches were the ratio of textures for the B and A2, the ratio of the pH for the B and A1 and the ratios of colour for the A1, A2 and B. Those not showing significant effects were the ratio of textures for the B and A1 and the ratio of the pH of B and A2.

The results in Table 5 allow determination of differences between patches. Patches 4 and 5 do not differ significantly with regard to any measured or derived variable even though they were identified as separate radiometric categories. As these patches were adjacent, they were amalgamated in the soils map. Some patches were similar for most properties but differed significantly for at least one variable, eg., patches 1, 2 and 7. These were kept separate and mapped as distinct soils categories.

The relationships between patches 1, 2, 3 and 7 identify the major disparity with the geological map, where patches 1, 2 and 3 are associated with the one radiometric class (7). Patchs 3 and 7 are identified as the same geological formation, but the soils differ greatly with patch 3 having a heavier texture, a uniform as opposed to duplex texture profile, and a darker colour. The properties of patch 7 are similar to the adjoining patches 1 and 2, and the western edge of patch 7 corresponds with a stream line. The topographical associations, the relationships between soil properties, and the nature of rock samples obtained in boreholes indicate that the radiometric map provides a more reliable information on materials than the geology map in the northwestern part of STA.

The results in Tables 4 and 5 are summarised in Table 6 for the soil classes identified as being significantly different. The numerical values for properties in the tables reflect the values for the pseudo-continuous variables used in the analysis, and the relationships between numeric values and the descriptions given in Table 2. The results in Table 6 do not give all the significant effects observed, but identify the main differences, and indicate the means of obtaining descriptions or labels for the mapped soil classes from the measures of soil properties. They also provide an indication of the nature as well as significance of the differences between the soils.

The final soils map composed of 16 classes is given in Fig. 2, with the soil class labels being given by the descriptions in Table 6. The sequencing of soil classes has been based on the depth of the A horizons within the groups or subgroups, with soils having deeper A horizons being assigned the larger numbers. The numerical identifiers for the soil classes in this map differ from those used in sampling (patches, Fig. 1) as indicated in Table 5.

The relationships between the radiometric signatures for the 16 soil classes are given in Fig. 3. This dendrogram, produced by clustering using Ward's incremental sum of squares, identifies four major groupings. Soil classes belonging to the same radiometric class are generally highly similar, as with soil classes1-2-3 and 11-12. The group represented by classes 1 to 7 effectively represents the Pmm geological formation, where this subdivides into two subgroups containing the soil classes 1-2-3 and 4-5-6 based on similarities in soil properties. Associations between the other groupings and the mapped geological formations are less obvious because some radiometric classes encompass two geological formations, and the geological map does not identify some significant areas of young alluvial deposits.

The soils map (Fig. 2) provides reliable discrimination between distinctive soil classes, as identified by the measured soil properties, but it does not identify all spatial patterns in soils. Significant differences in the depth of the A horizon related to catenary position exist for most soil classes (Table 5), and this information could be included to provide a higher resolution map. This was not done to maintain independence between the soil and terrain maps, and because the detail provided in Fig. 2 is probably close to the level required for management.

The significance of the soils mappings for land management is best evidenced by their relationship with the patterns of vegetation clearing and regeneration. The coarse textured soils of classes 9, 10, 14, 15 and 16 (Fig. 2) were never cleared. Hilly areas of classes 11 and 13 were never cleared, and many areas that were cleared are now densely wooded. Dense regeneration of trees has also occurred in classes 1, 2 and 3. Tree regeneration has also occurred in classe 4 but this has been sporadic and the woody vegetation is open. Tree regeneration has generally been very sparse for classes 5, 7 and 8.

Table 4 Significance levels, means and least significant differences for measured and derived variables in radiometric patches.

		Patch number for sampling																
	VR	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**16**	**17**	LSD
Th A1	2.5	1.7	2.4	2.4	4.8	3.7	7.0	1.7	6.4	2.4	2.6	5.6	3.2	4.1	5.3	5.0	3.3	3.4
Th A2	7.0	7.4	10.4	17.5	10.0	8.4	16.3	11.4	24.1	10.1	10.9	14.4	30.4	10.3	30.7	20.4	17.1	9.1
Th A	6.8	9.1	12.8	19.9	14.8	12.2	23.3	13.1	30.5	12.6	13.6	20.0	33.6	23.4	35.9	25.3	20.4	10.3
Tex A1	36.3	13.8	11.5	18.3	13.3	13.9	14.0	11.7	9.3	14.5	14.8	14.7	5.9	5.8	6.5	15.4	10.1	1.8
Tex A2	37.9	14.6	13.2	19.3	15.0	15.5	14.6	13.7	9.4	15.3	15.6	16.2	4.9	6.4	6.9	15.7	10.1	1.9
Tex B	17.4	19.7	20.5	20.2	20.3	19.6	19.6	20.0	16.6	20.7	20.1	19.9	14.1	17.3	11.9	18.8	15.2	2.2
Tex A2-A1	2.4	0.7	1.9	1.0	1.7	1.4	0.5	2.0	0.1	0.8	0.8	1.5	-1.1	0.6	0.4	0.2	0.0	1.4
Tex B-A2	5.9	5.2	7.3	0.9	5.4	4.1	5.1	6.3	7.2	5.4	4.5	3.7	9.2	10.9	4.9	3.2	5.1	2.5
pH A1	3.7	6.1	5.4	6.6	5.9	6.1	6.2	6.1	5.8	6.6	6.1	6.0	6.5	6.2	5.9	5.8	6.3	0.5
pH A2	4.1	6.3	5.2	6.3	6.0	6.2	6.1	5.3	5.3	6.3	5.9	6.0	6.3	5.8	5.3	5.8	6.1	0.7
pH B	9.2	6.6	5.8	7.4	6.4	6.7	6.4	4.7	5.5	7.3	6.2	7.4	6.4	6.1	5.5	5.8	6.0	0.8
pH B-A1	4.1	0.5	0.5	0.8	0.5	0.6	0.3	-1.3	-0.3	0.8	0.2	1.4	-0.1	-0.1	-0.4	-0.1	-0.3	1.3
pH B-A2	2.7	0.3	0.6	1.2	0.4	0.6	0.4	-0.6	0.2	1.0	0.3	1.3	0.1	0.4	0.2	0.0	-0.1	0.9
Col A1	4.9	3.3	4.4	3.4	3.2	3.3	3.0	3.3	3.4	3.6	3.7	3.5	4.4	2.5	4.4	4.2	2.8	0.8
Col A2	11.1	4.6	4.9	3.8	3.7	4.3	4.5	4.6	5.9	3.8	5.1	4.2	6.4	5.9	6.5	5.6	5.8	0.9
Col B	9.0	3.2	2.4	2.9	2.1	3.1	2.7	3.2	4.6	2.3	3.7	2.7	2.5	2.5	4.8	2.3	4.4	1.0
Col B-A1	6.6	-0.1	-2.0	-0.5	-1.0	-0.2	-0.3	-0.1	1.1	-1.2	0.0	-0.8	-1.9	0.0	0.4	-1.9	1.6	1.1
Col B-A2	4.2	-1.4	-2.5	-0.8	-1.6	-1.2	-1.8	-1.4	-1.4	-1.4	-1.4	-1.5	-3.9	-3.4	-1.7	-3.2	-1.4	1.0
Soil Class		**1**	**2**	**5**	**4**	**4**	**6**	**3**	**12**	**7**	**11**	**8**	**10**	**9**	**13**	**16**	**15**	

Th = thickness, Tex = texture, Col = colour, Class is the class number in the final soils map as used in Tables 5 and 7

Table 5. The main significant properties for the mapped soil classes.

Class	Depth A (cm)	Catena* (cm)	Texture A2		Texture B1		Texture B - Tex. A2		pH B1		Colour A2	
1	9.1	0.5	14.6	silty clay loam	19.7	medium clay	5.2	duplex	6.6	neutral -	4.6	coloured
2	12.8	1.5	13.2	silty loam	20.5	medium clay	7.3	duplex	5.8	slightly acid	4.9	coloured
3	13.1	-2.0	13.7	sandy clay loam	20.0	medium clay	6.3	duplex	4.7	acid	4.6	coloured
4	13.5	8.0	15.3	silty clay loam	20.0	medium clay	4.8	duplex	6.6	neutral -	4.0	coloured
5	19.9	-1.5	19.3	light clay	20.2	medium clay	0.9	uniform	7.4	neutral +	3.8	dark
6	23.3	13.0	14.6	silty clay loam	19.6	medium clay	5.1	duplex	6.4	slightly acid	5.9	pale
7	12.6	3.2	15.3	silty clay loam	20.7	medium clay	5.4	duplex	7.3	neutral +	3.8	coloured
8	20.0	-3.0	16.2	light clay	19.9	medium clay	3.7	gradational	7.4	neutral +	4.2	coloured
9	23.4	20.0	6.4	loamy sand	17.3	sandy clay	10.9	duplex	6.1	slightly acid	5.9	pale
10	33.6	13.0	4.9	fine sand	14.1	sandy clay loam	9.2	duplex	6.4	slightly acid	6.4	bleached
11	13.6	1.4	15.6	light clay	20.1	medium clay	4.5	gradational	6.2	slightly acid	5.1	pale
12	30.5	-19.0	9.4	fine sandy loam	16.6	sandy clay	7.2	duplex	5.5	acid	5.9	pale
13	35.9	13.4	6.9	clayey sand	11.9	loam	4.9	gradational	5.5	acid	6.5	bleached
15	20.4	6.5	10.1	clayey sandy loam	15.2	silty clay loam	5.1	duplex	6.0	slightly acid	5.8	pale
16	25.3	1.0	15.7	clay loam	18.8	light clay	3.2	gradational	5.8	slightly acid	5.6	pale
LSD	10.3		2.4		2.7		3.1		0.8		0.9	

* The catena effect is given as the difference in depth of the A horizons for the lower and mid - slope positions (lower slope - mid slope)

Table 6. Descriptions for the soil classes identified as significantly different, and mapped in Fig 2.

1	shallow duplex, coloured silty clay loam	**9**	intermediate duplex, pale loamy sand
2	thin duplex, coloured silty loam	**10**	thick duplex, bleached fine sand
3	thin duplex, coloured sandy clay loam	**11**	thin gradational, pale light clay
4	thin duplex, coloured silty clay loam	**12**	thick duplex, pale fine sandy loam
5	thin duplex, dark uniform light clay	**13**	thick gradational, bleached clayey sand
6	intermediate duplex, pale silty clay loam	**14**	
7	thin duplex, coloured silty clay loam	**15**	intermediate duplex, pale clay sandy loam
8	intermediate, gradational, coloured light clay	**16**	intermediate gradational, pale clay loam

DISCUSSION

The soil map derived from the radiometrics identify significant patterns that were not determined by conventional procedures. Moreover, the soil patterns derived from the radiometrics align with vegetation patterns, such as tree regeneration and weed and grass species. The radiometric data provide an opportunity to obtain and map soils information relevant to conservation as well as land management.

The patterns of tree regeneration relate generally to soil properties in that woody species dominate on the coarser textured soils with deep A horizons, however, there is currently insufficient knowledge to determine the extent to which the soil properties measured allow prediction of plant performance. The indications are that the occurrence of some weeds and grass species are related to the soil mappings, but such associations cannot be predicted from the measured soil properties. Use of the mappings in management therefore currently depends largely on field observations of plant response. For some applications, the existing soil descriptions should be supplemented by additional measurements of soil properties such as fertility, permeability / hydraulic conductivity, bulk density and shear strength. The value of the mappings provided in Fig. 2, additional to the information provided in Table 5, is that they allow supplementaty measurements to be obtained and applied in a cost effective manner.

The soil boundaries identified from the radiometrics broadly align with the boundaries of the geological formations, but significant differences exist. These differences appear to arise because:

a. Geological formations are not necessarily homogeneous with regard to parent material.

b. Soils are often composed of materials derived from a number of geological formations.

c. The locations of geological boundaries are often poorly defined and/or mapped.

The radiometric data appear to provide a better indication of the spatial distribution of parent materials than does the geology map, separating different depositional layers within formations, but there is still uncertainty as to the location of boundaries between different materials or soils. This uncertainty was reduced in the analysis of the radiometric data through the use of a measure of spatial association in the classification, where this helps identify and locate boundaries. The spatial measure appeared to increase the value of information derived from the low grade radiometric data.

The local adjustment to the georeferencing of the radiometric data used here attempted to match geological boundaries confirmed in the first phase study. The conclusion that the mappings for the soil classes broadly align with mappings for the geological formations therefore arises in part by definition. However, radiometric boundaries that could be readily associated with geological boundaries in the field were within the expected 500 metres (around one quarter of the flight line spacing). These observations indicated that errors were lowest in the flattest terrain, as would be expected.

The uncertainty in spatial positioning does not affect the conclusions made concerning the soils mappings in this study because the sampling was based on the defined positions. The statistical analyses of soil properties are valid for the given mappings, and these allow the conclusion that the radiometric provide a reliable means of mapping soils.

The low level of effects attributable to catenary position as opposed to parent material in determining soil patterns conflicts with most implementations of soil landscape mapping as these focus on topography, with parent material represented by broad geomorphological categories. These results indicate that, while landscape effects are significant, fine definition of parent material is required to reliably map spatial variations in soils.

The approach in this study attempts to balance the detail of soil description with the spatial resolution in mapping. The mapping resolution achieved here is enhanced relative to landscape mapping, but the soil descriptions have been simplified to make practical the sampling of a large number of sites. The results demonstrate the applicability of the approach, particularly given the test of reliability, but such simplifications can introduce limitations. However, as the variability about the means for the measured properties was always considerably larger than the resolution of the measurements, the simplifications adopted for the soil property descriptions did not significantly degrade the results.

The texture measurement is an example where the simplified descriptions could be expected to cause limitations, as this presents particle size distribution as a single vector. However, this simplifying assumption appears less limiting than the means of measurement. Texture measurements for the A2 horizon cover a wide range of values in the central portion of the texture range, and this provided good resolution. Conversely, measurements for the B horizon generally occur within few categories towards the end of the range, where this limits resolution. In such situations the nature of the variable may be more limiting than the method of measurement or categorisation, and an increase in the resolution of measurement may not improve results.

Catenary effects may have been underestimated in this study as only 3 catenary positions were measured to allow an increase in the number of transects. This may have decreased the resolution of catenary effects, but results from the first sampling involving 5 positions indicates that this is unlikely. However, crests had either deeply weathered or skeletal profiles, and such large differences for a position tend to mask catenary effects. This limitation can be resolved by improving the definitions of catenary positions, or by increasing the level of sampling to enhance the discrimination of interactions. Upgrading the stratification used for sampling by improving the definition of catenary position is most practical.

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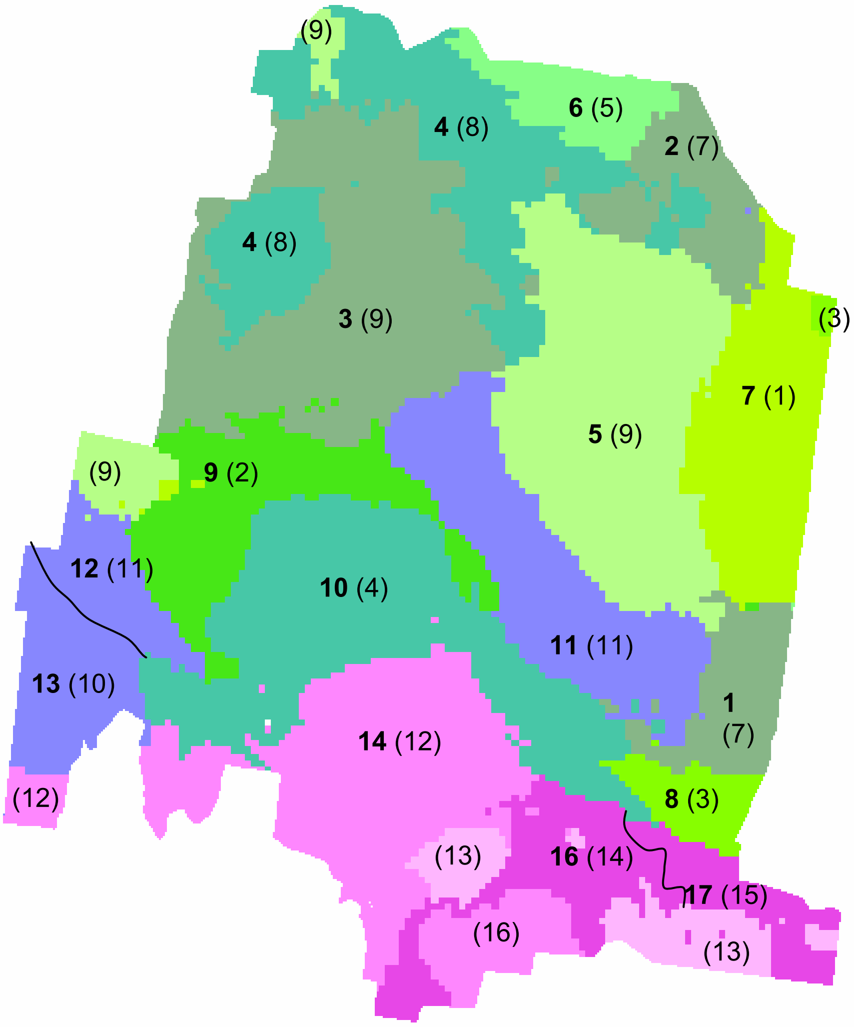

Figure 1.

Radiometric classes, and patch numbers for discrete areas of radiometric classes identified by the classification of the grided airborne gamma-radiation data (radiometrics). The radiometric class numbers are in brackets.

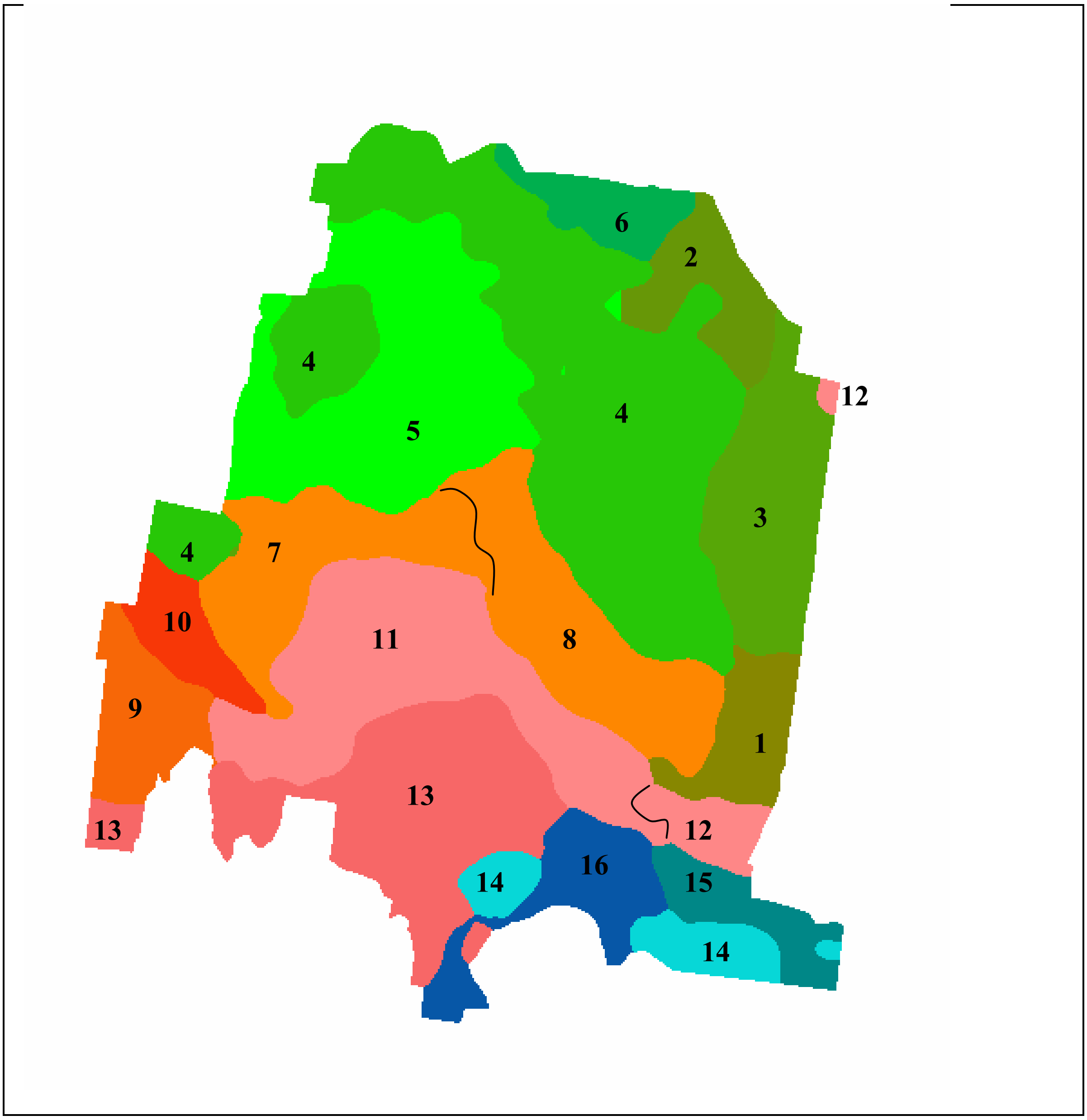

Figure 2.

Soil map for Singleton Training Area derived from the radiometric classes (Fig. 1), and the analysis of soil properties for radiometric patches. Descriptions for each class are given in Table 6, and soil properties in Table 5.

Figure 3. Relative similarity (%) of the radiometric signatures for the mapped soil classes.