Reprinted from

Symposium on Machine Processing of Remotely Sensed Data and Soil Information Systems and Remote Sensing and Soil Survey

June 3-6, 1980

Proceedings

The Laboratory for Applications of Remote Sensing

Purdue University
West Lafayette
Indiana 47907 USA

IEEE Catalog No.
80CH1533-9 MPRSD

STRATIFICATION OF LANDSAT DATA BY UNIFORMITY PRODUCTIVITY OF SOILS

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ABSTRACT

The goal of this study was to develop and verify methods to use Landsat data for mapping and quantifying the productivity of soil areas on which the annual yields of spring wheat exposed to the same weather conditions are generally different.

The study was done in two parts. First, a calibration study was done to determine which features visible on Landsat imagery were associated with different relative productivities. Then, in a two-part accuracy verification study, Uniform Productivity Area (UPA) boundaries were drawn on three map sheets (1:250,000 Canadian National Topographic System) and the relative productivity of each UPA within 25 townships in the Canadian Prairies were estimated. The boundaries were compared with known soil productivity area boundaries and the relative productivity ratings were compared with reported yields.

I. INTRODUCTION

A Crop Information System to predict production of wheat and other crops in Canada and elsewhere is under development by Agriculture Canada. In this System, crop production forecasts are made from acreage and yield estimates for specific politically bounded units (e.g. townships, rural municipalities, crop reporting districts and provinces). These estimates are generally made from sampled data selected to represent the larger political unit. However, the political unit is seldom uniform -- it often includes local subareas in which yields, acreages and crop signatures differ greatly, even under the same weather conditions. One major cause of these local differences is variations in soil properties.

An example of local differences are the different Landsat signatures of crops on different soils reported by U.S. investigators (e.g. Dalsted and DeVries[1], 1978; Myers et al[2], 1977). In general, these differences in signature have been attributed to differing contributions of the soil background to the combined crop-soil signature. However, in Canadian studies on growth and yields of spring wheat, where only plant density was estimated from Landsat Computer Compatible Tape (CCT) data and the signatures due to soil background were first eliminated, there were still large differences in the signature of wheat in different soil areas (Schubert et al[3], 1977; Mack et al[4], 1977). Since these wheat signature differences were correlated with yield differences (Schubert and Mack[5], 1978), they were attributed to spatial differences in soil productivity for wheat. Other studies have also shown that grain yields in the Canadian Prairies differ significantly on soils of different productive capacities, and some specific soils properties affecting productivity have been identified (Williams[6], 1975; Schubert and Chagarlamudi[7], 1978). In summary, variability in soil productivity appears to be a major factor which should be considered in sampling designs for estimating crop statistics. The development of methods for determining soil productivity ratings for wheat from digitally-enhanced Landsat data, and for mapping the productivities within politically relevant units, are presented in this paper.

II. THE STUDY AREA AND DATA

A. THE STUDY AREA

The study used data from three National Topographic System (Canadian) Map areas. For the calibration study, Landsat data and Land Systems maps for one 150 square mile area in each sheet were used. These calibration areas were representative of each of the predominant Great Group Chernozemic soils found in the Prairie Region of Canada (Table 1).

For the verification study, Landsat data for 20 townships in Wynyard and 5 in Swift Current map sheets were interpreted. Yield data published by Moss[8] for elevators points within each township were used as reference data for these townships.

Table 1. The Study Area.

Name and Number of NTS Map Sheet		Centre Frame Coordinates		Great Soil Group
Swift Current	72J	5560000mN	330000mE	Brown
Wynyard	72P	5740000mN	450000mE	Dark Brown
Melfort	73A	5860000mN	540000mE	Black
Melfort	73A	5630000mN	500000mE	Dark Gray
Melfort	73A	5630000mN	500000mE	Gray Luvisol

B. LANDSAT DATA

Landsat digital data on Canadian CCT's for three scenes obtained in July 1975 were used in this study, as follows:

2-0171-17154 July 12, 1975 Melfort
2-0171-17215 July 12, 1975 Wynyard
2-0172-17222 July 13, 1975 Swift Current

The data were standardized to remove differences between satellites, in Landsat sensor sensitivity, and in sun elevation. A special computer program was used to enhance differences in vegetation and soil colours on a simulated colour infrared image displayed on a colour television screen. The images were registered to a Universal Transverse Mercator projection map base, grid lines were inserted at 5 km intervals, and the registered data were presented on the screen at 1:50,000 scale for visual interpretation. A permanent record of the differences in colour, tone and features was obtained by photographing the screen with a 35 mm camera. All scenes were photographed and processed with standardized manual exposure controls so that differences in colour and tone produced by digital enhancement were maintained.

C. LAND SYSTEM MAPS

Soils in this study have been described and mapped into Land Systems, from field surveys and air photo data, as follows:

Melfort Rigby[9], 1973
Wynyard Shields _et al_[10], in Press
Swift Current Rennie and Acton[11], 1978.

III. THE STUDY

A. BACKGROUND

The goal of this study was to develop a method for mapping from Landsat data areas which consistently produce different yields of crops when exposed to the same weather. These differences are generally due to differences in the properties of the soils on which the crops are grown. Soil property differences affecting yields are referred to here as soil productivity differences. An area which does not exhibit differences in soil productivity is considered to be a uniform productivity area (UPA).

A second objective of this study was to express soil productivities quantitatively. Since weather and soil properties interact, the annual yields of crops are not an accurate quantitative measure of soil productivity. However, over a ten-year period, the average yields better reflect the actual soil productivity. A productivity value for any soil can be expressed in terms of the average yield for a ten-year period; it is valid only for that one period. Therefore, in this study, Productivity Classes were introduced to describe relative differences in average annual yields on different soils for any ten-year period. The actual yields for different periods will of course, vary with factors such as weather and technology trends.

As a preliminary part of this study, annual yield data from 1941 to 1952[8] for wheat were compared to soils occurring in different Land Systems ; the components of these Land Systems and their classes are listed in Table 2 (see also Figure 1). Stepwise linear regression was used to determine the contribution of each class of a Land System Component to productivity. (The years 1941 to 1952 were chosen because there were no rust epidemics nor major droughts in this ten-year period). For this period, the minimum difference in average yield among soils in different classes which was statistically significant was 2.7 bu/ac. Therefore, for this study, a productivity unit was defined as a 3.0 bu/ac average yield difference. Productivity classes differing by one productivity unit were then established for wheat. These Classes and their corresponding average annual yields for 1941 - 1952 are given in Table 3.

The Productivity Class for any soil area described by the classes of Land System Components listed in Table 2 can be determined by applying their corresponding coeficients to the equation developed by regression analysis, as shown below in Equation (1).

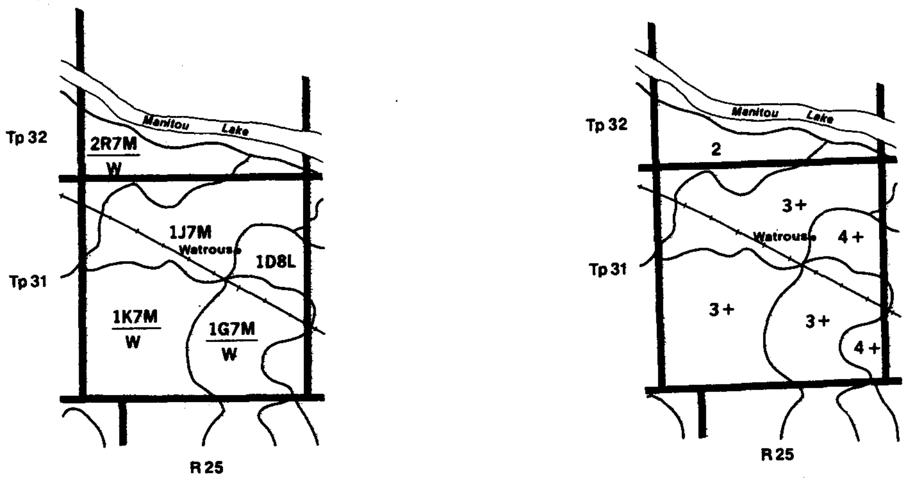
B THE CALIBRATION STUDY

For the calibration study, Land System Maps interpreted for relative productivity were overlain on Landsat imagery for four calibration areas each of 150 square miles (See Table 1) and then displayed on a colour CRT. The relative productivity maps were obtained by applying Equation 1 to Land System maps (Fig. 1). The calibration areas were selected to represent a wide range of Land Systems and, thus, of productivities.

<u>Calibration of Landsat Imagery of Different Soil Great Groups</u>. The most significant differences in soil productivity are the result of soils occurring in different soil-climatic

$$\text{Productivity Class} = PM_1 - TP_1 + SP_1 + (PM_2)(TP_2)\ (SP_2)\ (7.7 - SC_1 - 0.9TX_2) \qquad (1)$$

Figure 1 Land Systems[1] (part of the Wynyard Area) and their corresponding Productivity Classes Derived from Equation 1



Land Systems[1] Productivity Classes

MAP SYMBOL LEGEND

1G7M
W

Slope Class (1st Number)

1 0- 5%
2 5-10%
3 10-30%
4 30-60%

Surface Form (1st Letter)

J - Undulating
K - Hummocky knoll and kettle
H - Drainage Channel
D - Dissected

Soil Texture (2nd Number)

6 - Sandy loam
7 - loam
8 - clay loam
9 - clay

Genetic Material (2nd Letter)

M Morainal
L Lacustrine
F Fluvial
A Alluvium

W - Wind and Water Erosion Phase

1 A land system as employed in this study is defined as a recurring pattern of slope gradient, surface form, genetic origin of parent material, texture of surface soil and saline or erosional phases when present. Each of these components (i.e. slope gradient) consists of several classes as indicated in the above legend.

Table 2. Effect of Land System Component Classes on Average Yield of Wheat.

Component	Symbol[1]	Classes of the Component	Regression Equation[2] Coefficients (1)	(2)
Soil-Climatic Zone (Great Group)	Sc	Black Chernozemic	0	-
		Dark Gray Chernozemic	0.3	-
		Gray Luvisolic	1.7	-
		Dark Brown Chernozemic	3.0	-
		Brown Chernozemic	3.7	-
Texture	Tx	Clay	-	0
		Clay loam	-	1
		Loam	-	2
		Sandy loam	-	3
		Loamy sand	-	4
		Sand	-	5
Genetic Origin of Soil Parent Material	PM	Aeolian	1.1	1.0
		Morainal	1.9	0.8
		Lacustrine	1.0	1.0
		Fluvial	1.5	0.5
Modified by	PM	Shale (minor) ie Solód	2.4	1.3
		Shale (major) ie Solonetz	1.1	0.9
Slope Gradiant (Topography)	Tp	0-5%	0.0	1.0
		5-10%	0.8	1.1
		10-30%	0.6	0.9
Soil Phase	SP	Saline	0	0
		Eroded	0	0.5
		Stony	1.3	0

[1,2]See equation (1)

Table 3. Average spring wheat yields (1942-1951) and corresponding productivity classes.

Average Yield (1942-1951) (Bu/Ac)	Productivity Class[1]
7 - 9	1
10 - 12	2
13 - 15	3
16 - 18	4
19 - 21	5
22 - 24	6
25 - 27	7
28 - 30	8
31 - 33	9
34 - 36	10

[1]The symbols + and - may be used after the number to indicate the high or low end of the range.

zones. These five zones are listed in Table 4 according to the dominant soil Great Group in each. The four calibration areas include areas from each of the five zones.

In the first step of the calibration, differences in Landsat imagery for soils of the different zones were noted by comparing imagery of the four different areas. Since the Landsat data are digitally normalized to a common standard before display, the data obtained from different Landsat passes or at locations with different sun elevations, can be quantitatively compared. Therefore, colour and tone differences observed in crop and fallow fields on different Landsat scenes can be interpreted relative to each other. Also, the colour characteristics are preserved digitally and thus the calibration sites could be redisplayed throughout the study as reference imagery.

The average feature composition of each of the zones was compared to establish significant differences. Colour of the fallow fields and cropping patterns were found to be the most important differences associated with productivity differences in the different zones.

Table 4. Baseline Productivity Class Values for Soil-Climatic Zones.

Dominant Soil Great Group[1]	Map Sheet No.	Soil Productivity Class	Calibration Site Location		
			Tp[2]	R[2]	M[2]
Brown	72J	3	18	11	W3
Dark Brown	72P	5(-)	22	27	W2
Black	73A	7(-)	44	18	W2
Dark Gray	73A	6(+)	41	21	W2
Gray	73A	5(+)	42	21	W2

[1]Dominant in each soil-climatic zone.

[2]Township, Range, Meridian.

Differences in the average soil colour, of fallow fields among the calibration sites are striking, and correspond in productivity interpretation to differences in their relative productivity (Table 4). For example, the blackest soils on Landsat imagery correspond to the most productive region of Black Chernozemic soils. As the less productive (for wheat) Dark Brown Chernozemic and Dark Gray Luvisolic soils are encountered, they appear lighter in colour (blue-green on the enhanced imagery). Soils of the Brown Chernozemic zone which are still less productive are much lighter in colour (light to medium blue).

There are other characteristic differences in cropping pattern associated with the different zones which would assist in their recognition in unmapped areas of Canada. For example, rapeseed is absent from the Brown zone, sparsely present in the Dark Brown and forms up to twenty percent of the crop in the Black zone. Also the fallow patterns are characteristic (approximately 40 - 50% in the Brown zone, 30% in the Dark Brown, and 20% in the Black) in accordance with the climatic parameters and farming practices of each area.

Although the most significant boundaries of uniform productivity areas are those separating different soil zones, most of these boundaries have been mapped and the zones characterized through domestic and international mapping programs. Therefore, there is generally little need to locate boundaries or characterize the zones using Landsat data. Thus, in the remainder of the study it was assumed that the soil zone is known, either from indepent sources such as FAO maps or by previous interpretation of Landsat colour composite imagery obtained without digital processing.

Calibration of Landsat Imagery Within One Soil Zone. In the second calibration step, differences in productivities due to components of Land Systems other than soil zones were noted. For this calibration, one site of level to undulating (<5% slopes) lacustrine clay loam soil with no adverse soil phases was located and used for baseline calibration. (The Productivity Class of these soils on this site was the highest available and was represented in all calibration areas). These sites were used as a baseline for recognizing detraction features in less productive areas within each zone. The location of these sites and their Productivity Classes are given in Table 4.

The features on Landsat imagery associated with lower productivities of each area were determined. It was found that features were quite similar on imagery for the lower productivity areas of each zone -- that is, the same "cluster" of features associated with lower productivity relative to baseline in one site had a similar relative effect to the baselines of the other sites. These relationships were used to develop an interpretation key for use within each soil zone.

In the interpretation key, image features which were consistently associated with lower productivities were identified and ranked. The approximate percentage loss of productivity represented by each ranked feature was determined by comparison with the Productivity Class values of the Land Systems (Table 5).

C. VERIFICATION STUDY

Maps of boundaries separating Uniform Productivity Areas (UPA's) were interpreted from Landsat data and compared with boundaries on Land Systems maps. Landsat imagery for the entire Wynyard NTS map and for approximately half of the Melfort and Swift Current maps were interpreted according to the detraction features listed in Table 4 and UPA's were mapped.

Verification of Mapping. Landsat interpretation was done in several iterative steps. First, areas which appeared to have different clusters of features listed in Table 5 were separated by boundaries. Next the total percentage detraction for each cluster was estimated using the weightings in Table 5.

If the total detraction difference between two clusters was more than 15%, the boundary was recorded on a final map at 1:250,000 scale as a UPA boundary. If the total detraction difference between adjacent areas was more than 30%, the Landsat imagery of both areas was re-examined for features which might indicate additional UPA's. Boundary locations on the final maps were determined using the 5 Km grids on the UTM-registered digital data.

Accuracy of the final UPA boundaries was determined by comparing them with boundaries derived from Land Systems. Land Systems maps and Equation 1 were used to estimate the productivity class of each land system and thereby generate productivity area maps. More than 400 Land Systems or groups of Systems separating areas differing by at least one productivity Class were located

Table 5. Quantitative Interpretation Key For Calibration Soil Productivity On Enhanced Landsat Imagery.

Image Features Related to Productivity Detraction	Percentage of Baseline Productivity Subtracted for each Sub-feature: 0	5	10	15	20
1. Drainage Pattern	External			Internal	
2. Interruptions (sloughs, drainage channels, runways, stoniness)	None visible	Few, large	Some, mixed	Many, small	
3. Regularity of fields (size and shape)	Regular	Few, irregular, and due to obvious interruptions (lakes, roads, etc.) Sloughs	Many irregular, some pattern	Most irregular, no distinct pattern to fields	
4. Crop Colour A. Fields lighter than for other areas in soil zone	Usual colour distribution for zone	Slightly lighter	Much lighter many uneven		
B. Colour within fields uneven	Very uniform	Few fields uneven	Many, but not most, uneven	Most uneven	All uneven
5. Soil Colour	Usual for zone, uniform	Slightly lighter, even	Much lighter uneven	Much lighter, uneven	White, or very light in dark zone

Note: - Large Natural Areas are excluded and rate 0
- Small natural areas included with interruptions
- Minimum area delineated 3 mi^2

within the three areas mapped. These were superimposed on the UPA's, interpreted solely from Landsat data.

More than 95% of the boundaries separating UPA's mapped from Landsat resembled those on Land System maps prepared from soil survey and air photos. However boundaries from the two sources were only rarely totally coincident. Field investigations showed that in some cases, the boundaries drawn from Landsat features were more accurate than those interpreted from some of the older soil survey maps. This was particularly evident in the case of soil zonal boundaries mapped prior to the advent of air photos. Most of the major discrepencies between UPA and Land System boundaries occurred around Provincial Parks, Indian Reservations and Cities.

<u>Accuracy of Productivity Ratings</u>. Productivity Classes were assigned to the UPA's mapped from Landsat in the previous section using the Interpretation Key (Table 5). The classes were assigned by estimating the total percentage detraction from the baseline productivity class for a soil zone (Table 4). This was done by comparison of Landsat imagery with baseline calibration site imagery for the same soil zone as previously described.

Productivity classes of UPA's occurring within 25 townships (900 mi^2) were derived from Landsat data. (Approximately 500 mi^2 were in the Dark Brown Zone, 200 mi^2 the Brown zone, 150 in the Dark zone and 50 in the Gray Luvisolic zone). The extent of area of each UPA occurring within each of the 25 townships (36 mi^2) was measured. A Productivity Class average was calculated for each township from the Productivity Class values estimated for each UPA present and weighted for its relative area in the township (Table 6).

Table 6. Calculating the Productivity of a Township in which Lanigan is Located.

Relatively Productivity Class	Area of Township Occupied
5+	30%
3+	60%
4-	5%
6-	5%
4 weighted average score	100%

Verification Productivity Classes for each township were taken directly from the reported yields for Wheat delivered to elevators points in each township. The average reported yields for 1941-1952 were converted to Productivity Classes using Table 3 and were then compared with the Productivity Classes interpreted from Landsat data.

Correlation coefficient between the 25 productivity values estimated using Landsat data in combination with Table 4 and the productivities calculated from the yields reported for the townships was 0.93. The average difference between the reported and the estimated productivities was 0.33 Productivity Units and the standard deviation of the means was 0.23 Units.

IV CONCLUSIONS

There is a high correlation between productivity detraction features recognizable on enhanced Landsat data and the productivities of soils expressed by the average yields of spring wheat. Furthermore, areas bounded by factors recognized from other studies as significant for soil productivity are also recognized on Landsat data as discrete areas. Thus, it can be concluded that differences in soil productivities can be quantified and mapped on Landsat data.

There are, potentially, many applications for maps of quantified Uniform Productivity Areas. They can in fact, be used for some applications in place of or to compliment Land System maps since so many of the factors interpreted on the UPA maps are the same as those identified on the Land System maps. Overlaying UPA maps on Land System maps also provides a more objective grouping individual Land Systems areas which have similar long term productivities. In areas where no Land Systems map exist, Landsat data can be used to derive a lower resolution substitute with some unique applications. On the other hand, Land Systems maps can be used to establish boundary conditions of UPA's partially hidden by clouds.

In one application, UPA maps are used to select training-sample areas for computer classification of spring wheat on Landsat data. These maps are very suitable for this in areas where spring wheat is grown because the signature of wheat varies so greatly with its potential yield; this is, in turn, controlled by soil productivity -- just the factor mapped. While Land System maps, where they exist, may also be used for this purpose, the System components with classes which do not detract significantly from baseline productivity must be grouped.

Maps of UPA's can also be used to improve yield and production estimates for large areas. When sample data are used to estimate either yields or crop areas, the quantified relative productivities ratings of the UPA's can be used to aggregate the sample site data more effectively. For example, relatively few field sample estimates are required to give an accurate aggregated estimate for a county, or even a crop district, when the relative productivities of all UPA's in the county or district are known, including those for the sample fields. Conversely, when yield estimates are only available for the larger areas, as is the case with many yield model estimates presently used, better production estimates may be obtained when that yield estimate is first stratified by UPA ratings, then combined with the acreage estimates for each UPA, and then the UPA production estimates reaggregated for the larger area.

In conclusion, the methods described here for stratifying soils by productivity and for mapping the resultant Uniform Productivity Areas on geometrically corrected Landsat data registered to map scales, provide a useful new tool for improving sampling designs.

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Alex Mack is a research scientist with the Land Resource Research Institute of Agriculture Canada and currently acting head of the Agrometeorology Section of the Institute. He holds a Ph.D. degree in Agronomy. He has more than 20 years experience in soil fertility studies in various climatic regions, yield estimation, crop productivity and remote sensing. Dr. Mack has published more than 50 papers in scientific and technical journals. For the past few years, he has been responsible for advising Agriculture Canada in developing a crop information system for Canada using remotely sensed and weather data. He has been chairman of the Agriculture Working Group of the Canadian Advisory Committee on Remote Sensing since its inception in 1972.