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INVESTIGATION OF BOUNDARY PIXEL HANDLING PROCEDURES

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16. Abstract

Several methods of extracting quasi-fields from Landsat data are being considered as a component of future proportion estimation procedures. All known methods of extracting quasi-fields leave some portion of the image unprocessed. The boundary pixels which remain are generally a biased portion of the scene, and they are therefore potential error sources in proportion estimation. In this paper the boundary pixels are divided into three general classes. The relative size of each class is tabulated, and several methods are proposed for estimating the proportion of small grains in the set of boundary pixels.

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TABLES

1. INTRODUCTION

Boundary pixels have been a major source of labeling errors since the adoption of Procedure 1 which replaced field labeling with dot labeling at the start of the third phase of the Large Area Crop Inventory Experiment (LACIE). Terms such as "border," "edge," "mixed," and "misregistered" have been used to describe various classes of boundary pixels. All these terms, as well as the term "boundary pixel," have ambiguous and confusing definitions.

In this paper, the boundary pixels as observed in the spatial clustering algorithms described in reference 1 are considered. To define the boundary pixels, each acquisition to be processed is stratified into vegetated and nonvegetated subsets. After this stratification is complete, interior and boundary pixels of each subset are found. The interior pixels of these subsets are the pixels which have the property that all four horizontal and vertical neighbors belong to the same subset as the pixel in question. On a single acquisition, the boundary pixels are simply the noninterior pixels. The complete set of boundary pixels considered in this paper are the pixels which fail to be interior pixels on any of the acquisitions used.

These boundary pixels are divided into classes for further study. In section 2, these classes of boundary pixels are defined and their relative sizes are compared. In section 3, several methods of estimating proportions within the set of boundary pixels are proposed and compared. Conclusions and recommendations are in section 4.

2. TYPES OF BOUNDARY PIXELS

The general class of boundary pixels between areas of vegetation and nonvegetation reported on in this study was obtained as described in section 1. The data used in this study consisted of eight Landsat segments taken from the northern and southern U.S. Great Plains during crop years 1977 and 1978. The segments and acquisitions used are listed in table 2-1.

The boundary pixels in this data set were then divided into three categories as follows:

1. The perimeter boundary pixels are boundary pixels that are easily associated with a vegetated or nonvegetated field and lie in the perimeter of that field. These can be easily identified in an automated procedure because they are simply the boundary pixels which are neighboring on an interior pixel.
2. The linear boundary pixels are boundary pixels that are not readily identified with any field, but tend to lie in a line falling between two fields. To determine which boundary pixels are linear in nature, the perimeter boundary pixels are first removed from the general class of boundaries, and then the maximal connected subsets of the remaining boundary pixels are found. (In reference 1, it is stated that a set of pixels is connected if for each pair of points p and q in the set there exists a sequence $\{X_i\}_{i=o}^{n}$ of points in the set such that $X_0 = p$, $X_n = q$, and X_i and X_{i-1} are either horizontal or vertical neighbors for $i > o$.) The linear boundary pixels are those that belong to connected subsets of the nonperimeter boundaries which have no interior pixels.
3. The remaining boundary pixels then belong to connected subsets of the nonperimeter boundaries which do have interiors. These are called interior boundaries herein, and they can be interpreted as being those boundary pixels which lie in contiguous regions large enough to represent fields.

To begin this study, each acquisition of each segment in table 2-1 was treated independently. The boundary pixels in each acquisition were classified into

TABLE 2-1.- SEGMENT LOCATIONS AND ACQUISITIONS

Segment	Crop year	County, state	APU	Acquisition Julian dates
1005	1977 or Phase III	Cheyenne, Colorado	10	76254 76326 77159 77177
1059	1977 or Phase III	Ochiltree, Texas	9	76307 76325 77121 77157
1520	1977 or Phase III	Big Stone, Minnesota	19	77120 77156 77174
1803	1977 or Phase III	Shannon, South Dakota	17	76255 77123 77159 77178
1003	1978 or Transition Year	Adams, Colorado	10	77268 77304 78138 78227
1047	1978 or Transition Year	Stanton, Kansas	9	77266 78081 78117 78135
1154	1978 or Transition Year	Jones, South Dakota	17	78190 78226
1380	1978 or Transition Year	Redwood, Minnesota	15	78115 78169 78204 78241

the three categories described above, and the number of pixels in each category was recorded.

Table 2-2 gives the segment numbers, the acquisition numbers, the total percentage of each scene determined to be in boundary pixels, and the relative proportion of each type of boundary pixel. A cursory analysis of these data suggests that, for single acquisitions, the boundary pixels are quite manageable.

On the average, 26.8 percent of each scene consists of boundary pixels between vegetated and nonvegetated areas, but 78.3 percent of these boundary pixels are perimeter, and they are readily identified with a particular field. In fact, the boundary pixels can be made completely manageable on single acquisitions by using the boundary pixels to slightly alter the vegetation and nonvegetation stratification of each image.

This is done by the subroutine REGCL as described in reference 1, but the basic idea is that the nonperimeter boundary pixels of the vegetated subset are reassigned to the nonvegetated subset. This restratification causes a slight difference in the set of boundary pixels that are obtained. In the new set of boundary pixels, all of the nonperimeter boundary pixels are in the nonvegetated subset. These nonperimeter boundary pixels are then reassigned to the set of vegetated pixels, and this creates a vegetation and nonvegetation stratification in which the boundary pixels become almost entirely perimeter-type boundaries. Table 2-3 shows that, with this altered stratification, the average scene contains only 19.1 percent boundary pixels and that, on the average, 99.8 percent of these are perimeter boundary pixels and can therefore be assigned to fields.

Unfortunately, this does not solve the boundary pixel problem but only produces a method of assigning boundary pixels to groups of pure pixels on a single acquisition. The problem that remains is the difficulty introduced by misregistration of boundary pixels from acquisition to acquisition. When a boundary detected in each of two acquisitions is not registered, the set of

TABLE 2-2.- BOUNDARY PIXELS BETWEEN VEGETATED AND NONVEGETATED AREAS OF SINGLE ACQUISITIONS

Segment	Acquisition	Percent of scene in boundary	Percent of boundary that is perimeter	Percent of boundary that is linear	Percent of boundary that is interior
1005	76254	24.2	79.7	11.3	9.0
	76326	24.9	79.9	13.8	6.3
	77159	28.0	80.6	12.4	7.0
	77177	29.0	78.4	11.1	10.5
1059	76307	24.0	76.0	13.9	10.1
	76325	22.8	76.0	15.2	8.8
	77121	26.4	73.0	13.9	13.1
	77157	25.2	78.6	12.0	9.4
1520	77120	35.1	75.8	14.7	9.5
	77156	35.8	80.2	12.2	7.6
	77174	37.4	76.8	15.4	7.8
1803	76255	27.1	73.0	14.2	12.8
	77123	16.6	78.1	12.9	9.0
	77159	19.7	75.4	13.4	11.2
	77178	22.9	75.7	16.2	8.1
1003	77268	24.6	77.4	12.7	9.9
	77304	25.0	75.9	12.8	11.3
	78138	24.5	82.5	11.0	6.5
	78227	16.7	83.1	11.3	5.6
1047	77266	24.3	83.0	10.7	6.3
	78081	20.5	88.4	8.6	3.0
	78117	22.0	86.6	9.5	3.9
	78135	25.2	86.8	9.5	3.7
1154	78190	24.7	81.3	10.7	8.0
	78226	26.7	79.4	15.0	5.6
1380	78115	38.6	60.5	15.4	24.1
	78169	30.1	79.0	14.0	7.0
	78204	36.2	72.9	13.5	13.6
	78241	38.0	76.4	13.8	9.8

TABLE 2-3.- BOUNDARY PIXELS BETWEEN VEGETATED AND NONVEGETATED AREAS OF SINGLE ACQUISITIONS AFTER RESTRATIFICATION

Segment	Acquisition	Percent of scene in boundary	Percent of boundary that is perimeter	Percent of boundary that is linear	Percent of boundary that is interior
1005	76254	18.3	99.9	0.1	0.0
	76326	17.6	99.8	0.2	0.0
	77159	20.5	99.9	0.1	0.0
	77177	20.7	99.7	0.3	0.0
1059	76307	16.6	99.9	0.1	0.0
	76325	15.4	99.8	0.2	0.0
	77121	17.1	99.8	0.2	0.0
	77157	18.1	99.9	0.1	0.0
1520	77120	24.1	99.8	0.2	0.0
	77156	26.0	99.9	0.1	0.0
	77174	26.0	99.9	0.1	0.0
1803	76255	18.3	99.8	0.2	0.0
	77123	11.9	99.9	0.1	0.0
	77159	13.2	99.9	0.1	0.0
	77178	15.3	99.8	0.2	0.0
1003	77268	17.3	99.9	0.1	0.0
	77304	17.2	99.9	0.1	0.0
	78138	18.7	99.9	0.1	0.0
	78227	12.7	100.0	0.0	0.0
1047	77266	19.0	99.9	0.1	0.0
	78081	17.2	99.9	0.1	0.0
	78117	17.7	99.8	0.2	0.0
	78135	20.6	99.9	0.1	0.0
1154	78190	18.4	99.9	0.1	0.0
	78226	19.6	99.8	0.2	0.0
1380	78115	24.6	99.8	0.2	0.0
	78169	20.8	99.8	0.2	0.0
	78204	24.6	99.7	0.3	0.0
	78241	26.6	99.7	0.3	0.0

multitemporal boundary pixels must consist of the boundary pixels on each acquisition. The boundary then grows in thickness with each additional acquisition.

As a result, the proportion of linear and interior boundaries increases as new acquisitions are considered. Table 2-4 shows this increase in both total and nonperimeter boundary pixels when two, three, and four acquisitions are processed. Note the decrease in the percentage of boundary pixels in the perimeter class. For processing four acquisitions, this shows that the set of boundary pixels has increased to an average of 48.8 percent of the scene, while the average proportion of perimeter boundaries has dropped to 66.4 percent. This leaves approximately 16 percent of each scene in the categories of linear and interior boundary pixels.

The perimeter boundary pixels can readily be assigned to fields of multitemporally pure pixels, but a considerable bias can exist in the proportions of a given crop type within the remaining boundary pixels when compared to the proportions within the full segment. Thus, the pure pixels themselves can be a biased subset of the scene. In the next section, several methods of estimating the true crop proportions in the remaining set of boundary pixels are discussed and compared.

TABLE 2-4.- ACCUMULATION OF MULTITEMPORAL BOUNDARIES

(a) Percent of scene that is boundary by number of acquisitions:

Segment	Two acquisitions	Three acquisitions	Four acquisitions
1005	31.7	43.9	53.2
1059	25.8	37.2	46.8
1520	42.4	52.9	--
1803	27.6	34.6	42.0
1003	29.1	40.9	46.3
1047	30.8	37.8	43.9
1380	38.7	51.0	60.8

(b) Percent of boundary that is perimeter by number of acquisitions:

Segment	Two acquisitions	Three acquisitions	Four acquisitions
1005	88.9	75.2	65.9
1059	81.2	62.8	68.8
1520	83.3	67.0	--
1803	90.2	80.1	73.1
1003	84.6	76.5	69.1
1047	85.0	71.8	63.5
1380	82.0	69.2	58.2

(c) Percent of boundary that is linear by number of acquisitions:

Segment	Two acquisitions	Three acquisitions	Four acquisitions
1005	8.2	10.4	8.7
1059	13.3	9.1	7.3
1520	10.3	9.9	--
1803	7.3	10.2	9.0
1003	12.7	12.4	9.2
1047	13.1	12.2	9.9
1380	10.3	0.7	5.3

(d) Percent of boundary that is interior by number of acquisitions:

Segment	Two acquisitions	Three acquisitions	Four acquisitions
1005	2.9	14.4	26.4
1059	5.5	28.1	23.9
1520	6.4	23.1	--
1803	2.5	9.7	17.9
1003	2.7	11.1	21.7
1047	1.9	16.0	26.6
1380	7.7	20.1	36.5

3. ESTIMATING PROPORTIONS

In this study, the bias in the small grains proportions among the set of boundary pixels is considered. The perimeter boundary pixels need not be considered because they are readily assigned to fields, and they can be used in estimating the small grains proportions within the pure areas. The boundary pixels under consideration then are the linear and interior types. As was noted in the previous section, these nonperimeter boundary pixels are the result of misregistration of the perimeter boundaries obtained on individual acquisitions.

In some cases, these boundaries can become very thick. It seems reasonable that, for field-size estimation purposes, some decisions could be made concerning field membership of these pixels, even though spectrally they are not samples of any one field. Here the assumption is made that if one of these nonperimeter boundary pixels' neighbors is adjacent to only one field, then that field has been undersampled because of registration problems (since the pixel must be in the perimeter of that field on one of the acquisitions). Therefore, the nonperimeter boundary pixels which neighbor on only one field can be logically assigned to that field for proportion estimation purposes.

In practice, this procedure reduces the size of the unassigned boundary pixels to an average of around 8 percent of the scene. The ways of estimating the small grains proportions within these remaining boundary pixels will now be considered, assuming that no problem exists in obtaining proportions for the part of the image assigned to fields.

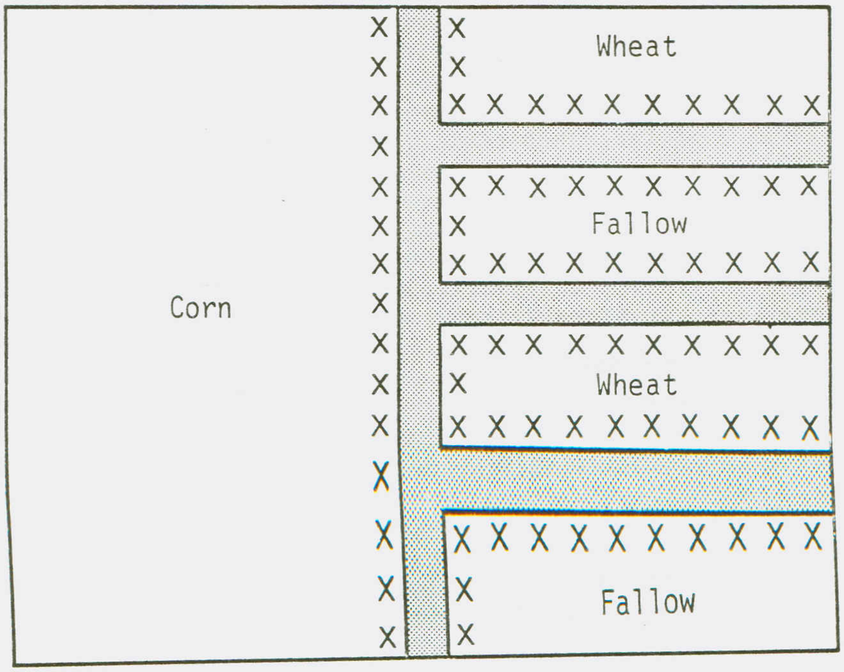
Four methods of estimating the proportion of small grains in the remaining boundary area are considered. Each method requires that the fields obtained in the clustering procedure be labeled. The four methods are:

1. Total the populations of those fields labeled small grains and divide this by the number of pixels assigned to fields. This assumes that there is no bias included by the field extraction.

2. Count the number of perimeter boundary pixels belonging to fields labeled small grains which are adjacent to the remaining boundary pixels and divide this by the total number of perimeter boundary pixels which are adjacent to the remaining boundary pixels. This is an attempt to model the contribution of field-size differences to the bias in the boundary sample. Figure 3-1 gives a hypothetical example of the kind of bias this attempts to remove. The pixels marked with an X are used to estimate the proportions in the shaded areas.
3. Divide the number of fields labeled small grains by the number of fields. This treats the boundary pixels as if they were fields having the same probability of being small grains that had been observed in the usual fields.
4. The final method is a combination of methods 2 and 3, which is to stratify the remaining boundary pixels into linear and interior types. Method 2 is applied to the linear boundary pixels, and method 3 is applied to the interior boundary pixels, producing a stratified estimate.

These methods were applied to the boundary pixels which remained after clustering the data shown in table 2-1 using the spatial methods discussed here and in reference 1. Each field was assigned the label corresponding to the predominant ground truth crop code of the pixels within the field. Table 3-1 shows the ground truth proportion of small grains among the boundary pixels for each segment, and the estimates obtained from the four methods discussed above with the bias and root mean square error (RMSE) observed using each method. The stratified method, method 4, is clearly superior to the first three methods in terms of overall bias and RMSE.

After using these methods to estimate the small grains proportions among the boundary pixels and using method 1 to estimate the small grains proportions among the pixels assigned to fields, a stratified estimate of the small grains proportions in each scene can be obtained. The final estimates obtained using these methods to estimate proportions among the boundary pixels are presented in table 3-2, along with the bias and RMSE associated with each method. These results imply that, when aggregated across segments, any reasonable method will work equally well when given the size of the boundary class used here.



Ground truth proportions: corn, 50%; wheat, 25%; fallow, 25%.

The cornfield contains 150 pixels.

The wheat and fallow fields contain 30 pixels each.

The wheat proportion in fields is 60/270, which is 22.2%.

There are 33 X-pixels in wheat fields.

There are 81 X-pixels total.

This leads to an estimate of 33/81, which is 40.7% of the boundary pixels that should be wheat.

There are 35 boundary pixels in this scene.

Thus, 14.25 of these boundary pixels should be wheat.

This leads to an estimate of (60 + 14.25)/(270 + 35), which equals 24.3% of the scene as wheat.

Figure 3-1.- Modeling field size contribution to boundary pixel bias.

TABLE 3-1.- PERFORMANCE OF ESTIMATION METHODS APPLIED TO BOUNDARY PIXELS

Segment	Ground truth proportion of SG in the boundary	Method 1 estimate of boundary	Method 2 estimate of boundary	Method 3 estimate of boundary	Method 4 estimate of boundary
1005	43.82	36.07	40.99	42.07	41.78
1059	42.28	46.98	49.00	43.55	44.83
1520	27.92	29.10	29.17	25.69	26.73
1803	3.91	3.86	3.91	2.49	2.97
1003	14.29	20.60	16.15	15.94	16.00
1047	39.21	36.23	42.84	30.74	34.02
1154	30.59	19.74	27.22	37.16	33.19
1380	10.42	11.71	12.89	11.98	12.10
Bias		-1.08	1.22	-.35	-0.10
RMSE		5.60	3.33	4.06	2.56

TABLE 3-2.- PERFORMANCE OF ESTIMATION METHODS APPLIED TO THE SEGMENT PROPORTION ESTIMATION

Segment	Ground truth proportion of SG in the segment	Method 1 segment estimate	Method 2 segment estimate	Method 3 segment estimate	Method 4 segment estimate
1005	37.25	36.07	36.49	36.59	36.57
1059	45.76	46.98	47.12	46.73	46.83
1520	30.02	29.10	29.12	28.79	28.88
1803	3.20	3.86	3.88	3.78	3.81
1003	21.09	20.60	20.27	20.29	20.29
1047	35.40	36.23	36.72	35.82	36.06
1154	20.70	19.74	20.20	20.82	20.57
1380	9.83	11.17	11.37	11.27	11.28
Bias		+0.06	+0.24	+0.10	+0.13
RMSE		0.99	1.05	0.88	0.90

4. CONCLUSIONS AND RECOMMENDATIONS

The problems encountered with boundary pixels seem to be related more to registration problems than to a mixture of classes within pixels. This has a significant bearing on the accuracy that can be obtained from pixel labeling procedures. Two problems should be noted here.

First, the registration error that occurs between boundary pixels also causes pure pixels to shift within a field to the same extent. Therefore, pure pixels may serve as samples of different areas within the same field from acquisition to acquisition. Sampling a good stand of wheat on one acquisition and an adjacent small water hole on the next could degrade the spectral values for such a pixel. Any pixel labeling procedure would be difficult in this situation without the benefit of information about the entire field from which this pure pixel was taken.

If this possibility seems too remote to worry about, consider the following crude approximation of the size of the problem. Suppose two acquisitions of the same segment are given. Let A denote the percentage of the full scene which appears as a boundary pixel in the first acquisition but not the second. Let B denote the percent- age of the full scene which appears as a boundary in both acquisitions, and let C denote the portion of the full scene which appears as a boundary in the second acquisition but not in the first.

Table 2-3 shows that the average size of the boundary class in one acquisition is 19.1 percent, and table 2-4 shows an average of 32.3 percent combined boundaries using two acquisitions. This yields the following approximately true equations:

$$A + B = 19.1$$

$$B + C = 19.1$$

$$A + B + C = 32.3$$

Solving this system of equations yields B = 5.9. Thus, 5.9/32.3 18.3 percent of the combined boundary detected from two acquisitions is detected on both acquisitions. The nonperimeter boundary pixels that are observed using two acquisitions must be a subset of this 18.3 percent since only perimeter-type boundary pixels occur within single acquisitions.

The nonperimeter boundary accumulated using two acquisitions averages 15.0 percent of the total boundary given in table 2-4. This says that 15.0/18.3, or about 82 percent, of the pixels observed on both acquisitions shifted positions and created nonperimeter boundaries. This indicates that the probability is about 80 percent that any pixel does not represent the same area of land from one acquisition to the next.

A second problem that occurs in pixel labeling procedures is that the ground truth that is used to estimate accuracy has the same registration problems. If it is assumed that the ground truth takes the form of another acquisition and that the ground truth small grains on that acquisition are the only vegetated pixels on that acquisition, then this leads to the assumption that 19 percent of the scene consists of pixels which lie in a perimeter of areas of ground truth small grains or other and that 80 percent of those shift one or more pixels when compared to the imagery used in labeling. If it is assumed that 50 percent of those that shift change classes and 50 percent remain in the same class, this leads to a conservative estimate that 7 percent of the ground truth is labeled inappropriately. Therefore, some sort of quasi-field labeling seems to be a logical alternative. Bryant (ref. 2) reinforces this conclusion.

The problem of sampling bias included by field-finding algorithms does not appear to be significant in this study. Perhaps this is because the algorithms used here reduced the boundary class considerably before trying to estimate this bias, or perhaps there is no significant boundary bias in this particular crop type. If in the future there does appear to be a significant bias involved in such a subsetting operation, the methods presented in section 3 appear to be a promising solution.

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