APPLICATION OF SATELLITE DATA TO CROP AREA ESTIMATION AT THE COUNTY LEVEL

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Michael E. Bellow, USDA/NASS
Research Division, 3251 Old Lee Highway, Room 305, Fairfax, VA 22030

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I. INTRODUCTION

The National Agricultural Statistics Service (NASS) of the United States Department of Agriculture has published county estimates of crop acreage, crop production, crop yield and livestock inventories since 1917. These estimates assist the agricultural community in local decision making and are also useful to agribusinesses. The primary source of data for agricultural commodity estimates has always been surveys of farmers, ranchers and agribusinesses who voluntarily provide information on a confidential basis. However, surveys designed and conducted at the national and state levels are often inadequate for producing reliable information at the county or small domain level. Therefore, supplementary data sources such as NASS list frame control data, previous year estimates and Census of Agriculture data are often used to improve county estimation. Earth resources satellite data represents a useful ancillary data source for county level estimation of crop planted and harvested area. The basis for improved estimation accuracy using satellite data is the fact that, with adequate coverage, all of the area within a county can be classified to a crop or ground cover type. The accuracy of the estimates depends upon how accurately the satellite data are classified to each crop.

NASS has used or considered several regression based estimators for small area crop acreage estimation with ancillary satellite data. These estimators use stratum level counts of pixels classified to crops. From 1976 to 1982, NASS used the Huddleston-Ray estimator (Huddleston and Ray, 1976). In 1978, the Cardenas family of estimators (Cardenas, Blanchard and Craig, 1978) was considered but not adopted. From 1982-87, the Agency used the Battese-Fuller estimator (Battese, Harter and Fuller, 1988) for county level estimation of major crops in the Midwestern grain belt with Landsat Multispectral Scanner (MSS) data. The same method was used to calculate county estimates of rice, cotton and soybeans in the Mississippi Delta region in 1991-92 with Landsat Thematic Mapper (TM) data. Research has recently begun to consider non-regression estimators based on overall (across strata) counts of classified pixels. This report discusses two such estimators and compares them with the Battese-Fuller estimator.

Graham (1993) provides a description of the methodology used to obtain classified pixel counts and generate state and regional level crop acreage estimates. Some knowledge of those concepts is helpful in the upcoming discussion.

II. BATTESE-FULLER ESTIMATOR

The Battese-Fuller approach to crop area estimation at the county level is an extension of the regression methodology used for state level estimation. The Battese-Fuller estimator (BFE) utilizes the analysis district (multi-county) level regression, but incorporates an additional term that accounts for county (random) effects.

The Battese-Fuller model was first developed in the general framework of linear models with nested error structure (Fuller and Battese, 1973), and later applied to the special case of county crop area estimation (Battese, Harter and Fuller, 1988). In state level estimation, a group of counties and parts of counties covered by one or more satellite scenes comprises an analysis district. Analysts compute regression relationships between NASS survey reported acreages and counts of classified pixels, using area frame sample units (segments) within each analysis district. The Battese-Fuller model assumes that segments grouped by county have the same slope relationship with classified pixels as the analysis district, but the intercept term is different. One can apply the model within an analysis district for any land use stratum where a valid regression relationship has been found. The analyst computes stratum level Battese-Fuller area estimates for all counties and subcounties within each analysis district. For land use strata where regression is not feasible due to lack of adequate satellite coverage or too few segments, a domain indirect synthetic estimator is used.

For a given analysis district, the strata where regression is done are here referred to as regression strata and the remaining ones as synthetic strata. For convenience, the regression strata are labelled $h=1,\ldots,H_r$ and the synthetic strata $h=H_r+1,\ldots,H$, where H_r is the number of regression strata and H is the total number of strata in the analysis district. If a given county is partially contained in the analysis district, then the estimation formulas given below apply only to the included portion.

For each sample segment within a given stratum h in county c, the Battese-Fuller model specifies the following relation:

$$y_{hci} = \beta_{0h}+\beta_{1h}x_{hci}+\nu_{hc}+\epsilon_{hci},\ j=1,\ldots,n_{hc}$$

where:

- n_{hc} = number of sample segments in stratum h, county c
- y_{hci} = reported acreage of crop of interest in stratum h, county c, sample segment i
- x_{hci} = number of pixels classified to crop of interest in stratum h, county c, sample segment i
- ν_{hc} = county (random) effect for stratum h, county c
- ϵ_{hci} = random error in stratum h, county c, sample segment i
- β_{0h}, β_{1h} = analysis district level regression parameters for stratum h

The county effect and random error are assumed to be independent and normal, with mean zero and variances σ^2_{vh} and σ^2_{eh}, respectively. The random errors for segments within the district are assumed to be mutually independent. The county mean residuals are observable and given by:

$$\bar{u}_{hc.} = \bar{y}_{hc.} - \hat{\beta}_{0h} - \hat{\beta}_{1h}\bar{x}_{hc.}$$

where:

$$\bar{y}_{hc.} = (1/n_{hc})\sum_{i=1}^{n_{hc}} y_{hci}$$

$$\bar{x}_{hc.} = (1/n_{hc})\sum_{i=1}^{n_{hc}} x_{hci}$$

$\hat{\beta}_{0h}, \hat{\beta}_{1h}$ = least squares regression parameter estimators for stratum h

For a given county, the stratum level mean crop area per population unit (segment) is estimated by:

$$\bar{y}_{(BF),hc.} = \hat{\beta}_{0h} + \hat{\beta}_{1h}\bar{X}_{hc} + \delta_{hc}\bar{u}_{hc.}$$

where:

- $\bar{X}_{hc}$ = mean number of pixels per population unit classified to crop in stratum h, county c
- $0 \le \delta_{hc} \le 1$

The range of allowed values of the parameter δ_{hc} defines a family of Battese-Fuller estimators. If δ_{hc}=0, then the estimate lies on the analysis district regression line for the stratum. The value commonly used is the one that minimizes the mean square error for stratum h in county c (Walker and Sigman, 1982):

$$\delta^*_{hc} = n_{hc}\sigma_{vh}^2/(n_{hc}\sigma_{vh}^2+\sigma_{eh}^2)$$

In general, the variance components σ_{vh}^2 and σ_{eh}^2 are unknown and must be estimated. The Appendix gives estimators that are a special case of the unbiased estimators derived by Fuller and Battese (1973), using the "fitting-of-constants" method. They require that a given stratum contain at least two sample segments within the county in question; otherwise δ_{hc} is set to zero in the computation of the Battese-Fuller estimate.

The (unadjusted) stratum level estimator of total crop area in county c is:

$$\hat{T}_{(uBF),hc} = N_{hc}[\hat{\beta}_{0h} + \hat{\beta}_{1h}\bar{X}_{hc} + \delta_{hc}\bar{u}_{hc.}]$$

where:

N_{hc} = number of population units in stratum h, county c

The county estimates are often adjusted to sum to the district totals obtained in state level regression estimation. The adjusted stratum level Battese-Fuller estimator is:

$$\hat{T}_{(aBF),hc} = \hat{T}_{(uBF),hc} - (N_{hc}/N_h)\sum_{c=1}^{C} \delta_{hc}\bar{u}_{hc.}$$

where:

- N_h = number of population units in stratum h
- C = number of counties in analysis district

The adjusted Battese-Fuller estimator of total crop area in the regression strata of county c is:

$$\hat{T}_{(aBF),c} = \sum_{h=1}^{H_r} \hat{T}_{(aBF),hc}$$

Estimation of the variance of the BFE is described by Walker and Sigman (1982). Their estimator of mean square error, used to derive the variance estimator, is known to have a downward bias due to estimation of the variance components. A correction due to Prasad and Rao (1990) may be implemented in the future.

As mentioned previously, synthetic estimation is done in strata where regression is not viable. Since a county usually contains few segments in a given stratum, the stratum level sample mean crop acreage over the entire analysis district is used to compute a synthetic estimate. The estimate of crop area in synthetic stratum h, county c is:

$$\hat{T}_{(SYN),hc.} = N_{hc}\bar{y}_{h..}$$

where:

$\bar{y}_{h..}$ = mean reported crop area per sample segment in stratum h

The domain indirect synthetic estimator of total crop area in the synthetic strata of county c is then:

$$\hat{T}_{(SYN),c} = \sum_{h=H_r+1}^{H} \hat{T}_{(SYN),hc}.$$

with estimated variance:

$$\hat{\sigma}^2[\hat{T}_{(SYN),c}] = \sum_{h=H_r+1}^{H} N_{hc}^2 s_{yh}^2 (N_h - n_h)/N_h n_h$$

where:

$$s_{yh}^2 = (1/n_h - 1)\sum_{i=1}^{n_h} \sum_{c=1}^{C} (y_{hci} - \bar{y}_{h..})^2$$

The final county estimate is obtained by summing the regression and synthetic components:

$$\hat{T}_c = \hat{T}_{(BF),c} + \hat{T}_{(SYN),c}$$

The estimated variance of the final county estimate is computed by summing the variance estimates of the regression and synthetic components. The use of the analysis district level average to estimate county totals ignores county effects, so the synthetic component of a county estimate can have a significant bias.

Walker and Sigman (1982) studied the Battese-Fuller model using Landsat MSS data over a six county region in eastern South Dakota. At that time, NASS was using the Huddleston-Ray estimator (Huddleston and Ray, 1976), which simply replaced the analysis district level pixel mean in each stratum with the county level pixel mean in the regression equation. The county effect parameter of the Battese-Fuller model was highly significant for corn, the most prevalent in the region of the four crops considered. The study showed robustness of the Battese-Fuller family against departure from certain model assumptions, and provided the justification for replacing the Huddleston-Ray estimator with the Battese-Fuller estimator for operational county crop estimation.

III. PIXEL COUNT ESTIMATORS

As improved satellite sensors enable higher classification accuracy, the overall (across strata) count of pixels within an area classified to a given crop or cover type becomes more interesting. The overall pixel count represents a census of pixels covering the area in question and therefore is not subject to sampling error. However, there is a nonsampling error due to pixel misclassification. As a result, the overall pixel count (converted to area units) is generally a biased estimator of crop area. Adjustment factors based on sample level information can reduce the bias. Although a pixel count estimator could be a function of counts of pixels classified to many different cover types, this discussion will be restricted to estimators based on the number of pixels classified to the crop of interest only. A general expression for such an estimator is:

$$\hat{T}_c = \eta X_c$$

where:

X_c = number of pixels classified to crop of interest in county c
η = adjustment term

The adjustment term may be a function of the sample level classification data. The choice of adjustment term determines the specific estimator used. If the term is simply set to the area on the ground corresponding to one pixel, then the Raw Pixel Count Estimator (RPCE) is obtained:

$$\hat{T}_c^{(RPC)} = \lambda X_c$$

where λ is the conversion factor (area units per pixel) for the satellite sensor being used.

The RPCE is biased if the theoretical commission error (probability that a pixel classified to the crop of interest is from another cover type) and omission error (probability that a pixel from the crop of interest is classified to another cover type) are not equal. The combined ratio estimator (CRE), based on the estimator of the same name described in Cochran (1977), attempts to adjust for the bias. This estimator is conceptually simple, uses stratum level information to compute the adjustment term and has a readily available formula for estimating the variance. The CRE can be expressed as follows:

$$\hat{T}_c^{(CR)} = [(\sum_{h=1}^{H} N_h \bar{y}_{h..})/(\sum_{h=1}^{H} N_h \bar{x}_{h..})]X_c$$

$$= \hat{R}X_c$$

An estimator for the variance of the combined ratio estimator is derived from Cochran's population variance formula, valid for large samples:

$$\hat{\sigma}^2[\hat{T}_c^{(CR)}] = [X_c/X]^2 \sum_{h=1}^{H} [(N_h^2(1-f_h)/n_h](s_{yh}^2 + \hat{R}^2 s_{xh}^2 - 2\hat{R}s_{xyh})$$

where:

$$s_{xh}^2 = (1/n_h - 1)\sum_{i=1}^{n_h} (x_{hi} - \bar{x}_{h..})^2$$

$$s_{yh}^2 = (1/n_h-1)\sum_{i=1}^{n_h}(y_{hi}-\bar{y}_{h..})^2$$

$$s_{xyh} = (1/n_h-1)\sum_{i=1}^{n_h}(x_{hi}-\bar{x}_{h..})(y_{hi}-\bar{y}_{h..})$$

$f_h = n_h/N_h$

y_{hi} = reported area of crop of interest in stratum h, sample segment i

x_{hi} = number of pixels classified to crop of interest in stratum h, sample segment i

$\bar{x}_{h..}$ = mean number of pixels per sample segment classified to crop of interest in stratum h

X = total number of pixels classified to crop of interest

IV. EMPIRICAL EVALUATION

This section describes an empirical evaluation of the satellite based county crop area estimators described above, performed using data from Iowa and Mississippi. The Iowa data were from a 1988 research project, while the Mississippi data were from NASS's 1991 operational project in the Mississippi Delta region (Bellow and Graham, 1992). The quantity estimated was acreage planted to a crop.

The first application area is a nine county region in western Iowa with a high concentration of corn and soybeans. Ground data from NASS's 1988 June Agricultural Survey (JAS) were used for estimation, with a total sample size of 30 segments from two strata. The region was covered by one TM scene with an image date of July 25, 1988. The second area, a twelve county region in northwestern Mississippi, comprises two contiguous crop reporting districts that accounted for most of the state's cotton and rice production in 1991. Ground data from the 1991 JAS were used for estimation, involving 73 segments in four strata for cotton and 59 segments in two strata for rice. The analysis used multitemporal satellite data with image dates of April 1 and August 23, 1991. Two TM scenes from each date were needed to cover the region. For both regions, all seven spectral bands from each scene were utilized. The adjusted version of the Battese-Fuller estimator was computed in all cases.

For Iowa, the analysis used 30 segments, with 28 coming from stratum A (agricultural) and the other two from stratum B (agri-urban). Data from the segments in stratum A were used for the BFE, which was computed within the subset of that stratum covered by the TM scene. Parts of Calhoun, Crawford and Ida counties lay outside the TM scene. For the BFE, CRE and RPCE, synthetic estimation was applied within stratum A for the areas outside the scene. For the BFE, synthetic estimation was used in stratum B for all areas.

The strata in Mississippi where Battese-Fuller estimation was used for cotton were strata A (75-100% cultivated), B (51-75%), C (15-50%) and D (0-15%). The BFE was applied only in strata A and B for rice. Synthetic estimation was used in the other strata for each crop. The TM scenes covered all areas except for a small part of Yazoo county.

Tables 1 and 2 give the computed values of the satellite based BFE, CRE and RPCE for Iowa and Mississippi, respectively. For comparison, the survey based estimate (SYN) obtained by using synthetic estimation in all strata is also shown. Estimated standard deviations are given for the SYN, BFE and CRE. The official county planted acreage estimates issued by NASS's Iowa and Mississippi State Statistical Offices are also listed. These published estimates are based on additional survey and administrative data. The official county figures for Iowa are believed to be highly accurate indicators of corn and soybean acreage. Rice figures are not given for Issaquena, Quitman and Yazoo counties since Mississippi did not issue official rice estimates for those counties in 1991. Tables 3 and 4 give measures of estimator accuracy for the two states, computed based on the final official figures. The mean deviation (MD), root mean square deviation (RMSD), mean absolute deviation (MAD) and largest absolute deviation (LAD) are shown.

Comparing the standard deviations of SYN, BFE and CRE given in Table 1, it is seen that CRE had the lowest value for both corn and soybeans in all Iowa counties considered. BFE had lower variance than SYN in all counties for corn and all but one county for soybeans. Table 2 shows that in Mississippi, CRE had lower variance than BFE in eight of twelve counties for cotton and eight of nine counties for rice. For both cotton and rice, SYN had higher variance than BFE and CRE in each county.

Table 3 shows that for corn in Iowa, BFE had the lowest MAD and RMSD among the four estimators studied. However, RPCE had the lowest RMSD and MAD for soybeans. From Table 4, BFE showed the lowest MAD and RMSD for cotton in Mississippi, but CRE had the lowest MAD and RMSD for rice. For all four crops, the survey based estimator SYN showed the highest values of RMSD, MAD and LAD and is therefore clearly inferior to the other three estimators. The mixed results suggest that the relative performance of the three satellite based estimators may depend to a large degree on the specific crop. The mean deviation of BFE was negative for all four crops, suggesting a possible downward bias of this estimator.

V. SUMMARY

This paper described the current status of satellite based county crop area estimation in

NASS. The Battese-Fuller model is currently applied to compute county acreage indications provided to certain NASS State Statistical Offices. Estimators based on overall pixel counts have recently begun to receive attention. Empirical results for Iowa and Mississippi suggest that the CRE has lower variance than the BFE, while relative performance of estimators appears to be crop specific. The BFE and CRE both showed a negative bias in the study. Future research will explore properties of these estimators for different crops and other regions.

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APPENDIX. ESTIMATION OF BATTESE-FULLER VARIANCE COMPONENTS

The estimators of the Battese-Fuller variance components at the analysis district level represent a special case of the more general unbiased estimators derived by Fuller and Battese (1973). The variance component estimators are as follows:

$$\hat{\sigma}_{eh}^2 = [1/(n_h - C - 1)] \times \sum_{c=1}^{C} \sum_{i=1}^{n_{hc}} [y_{hci} - \bar{y}_{hc.} - \hat{\alpha}_h (x_{hci} - \bar{x}_{hc.})]^2$$

$$\hat{\sigma}_{vh}^2 = \max[0, s_{uh}^2 - (n_h - 2)\hat{\sigma}_{eh}^2]/(n_h - T_h)]$$

where:

$$\hat{\alpha}_h = \frac{\sum_{c=1}^{C} \sum_{i=1}^{n_{hc}} (x_{hci} - \bar{x}_{hc.})(y_{hci} - \bar{y}_{hc.})}{\sum_{c=1}^{C} \sum_{i=1}^{n_{hc}} (x_{hci} - \bar{x}_{hc.})^2}$$

$$s_{uh}^2 = \sum_{c=1}^{C} \sum_{i=1}^{n_{hc}} (y_{hci} - \hat{\beta}_{0h} - \hat{\beta}_{1h} x_{hci})^2$$

$$T_h = \frac{n_h \sum_{c=1}^{C} n_{hc}^2 \bar{x}_{hc.}^2 + (\sum_{c=1}^{C} n_{hc}^2)(\sum_{c=1}^{C} \sum_{i=1}^{n_{hc}} x_{hci}^2) - Q_h}{(n_h \sum_{c=1}^{C} \sum_{i=1}^{n_{hc}} x_{hci}^2) - n_h^2 \bar{x}_{h..}^2}$$

$$Q_h = 2 n_h \bar{x}_{h..} \sum_{c=1}^{C} n_{hc}^2 \bar{x}_{hc.}$$

The value of the quantity δ_{hc} that minimizes the mean square error of the Battese-Fuller estimator can then be estimated by:

$$\hat{\delta}_{hc}^* = n_{hc}\hat{\sigma}_{vh}^2/(n_{hc}\hat{\sigma}_{vh}^2 + \hat{\sigma}_{eh}^2)$$

Walker and Sigman (1982) provide expressions for the mean square error and mean square conditional bias of the stratum level Battese-Fuller estimator. Separate formulas are required depending upon whether the regression parameters are known or estimated. Variance estimators are derived from these formulas.

Table 1: County Estimates for Iowa 1988 (1000 Acres)

CORN:

County	Official	SYN	SD	BFE	SD	CRE	SD	RPCE
Audubon	100.0	112.4	6.5	92.2	3.2	93.6	2.1	100.6
Calhoun	133.0	144.9	8.3	133.2	3.9	134.4	2.9	144.2
Carroll	141.0	146.2	8.4	141.4	4.5	142.1	3.1	152.6
Crawford	147.0	183.2	10.6	152.7	4.7	155.1	3.2	164.9
Greene	125.0	145.9	8.4	130.0	3.9	132.8	2.9	142.7
Guthrie	98.0	151.3	8.7	106.3	5.2	107.8	2.4	115.8
Ida	112.0	111.4	6.4	107.0	4.0	107.0	3.8	110.3
Sac	136.0	148.1	8.5	138.3	4.0	139.6	3.1	150.0
Shelby	155.0	149.4	8.6	140.7	4.0	141.5	3.1	152.1

SOYBEANS:

County	Official	SYN	SD	BFE	SD	CRE	SD	RPCE
Audubon	70.7	74.0	7.5	69.9	4.6	70.4	2.1	74.8
Calhoun	150.0	95.4	9.6	145.0	5.8	136.9	4.0	145.2
Carroll	117.0	96.1	9.7	106.7	9.7	106.4	3.1	113.0
Crawford	106.0	120.4	12.1	106.9	5.8	108.1	3.1	113.8
Greene	143.0	96.1	9.7	117.5	5.4	109.6	3.2	116.3
Guthrie	77.5	99.5	10.0	64.4	7.0	78.8	2.3	83.7
Ida	75.2	73.3	7.4	76.4	5.3	76.1	4.3	78.2
Sac	124.0	97.3	9.8	112.9	5.5	108.8	3.2	115.5
Shelby	94.9	98.3	9.9	81.0	6.0	91.1	2.7	96.7

Table 2: County Estimates for Mississippi 1991 (1000 Acres)

COTTON:

County	Official	SYN	SD	BFE	SD	CRE	SD	RPCE
Bolivar	65.5	106.2	15.4	61.6	6.1	60.6	3.9	80.6
Coahoma	105.7	59.2	8.4	88.3	4.2	82.6	5.2	109.8
Humphrey	61.6	53.2	7.2	57.3	3.4	54.2	3.4	72.1
Issaquena	38.0	42.6	8.6	34.6	3.9	27.5	1.8	36.6
Leflore	79.2	68.8	9.6	87.8	3.5	83.4	5.3	111.0
Quitman	31.0	48.1	7.2	46.4	4.0	44.5	2.8	59.3
Sharkey	47.0	43.2	6.9	48.6	3.4	42.5	2.7	56.6
Sunflower	100.0	95.6	15.0	79.3	5.5	73.9	4.7	98.3
Tallahatchie	64.2	68.9	10.5	67.9	4.9	60.3	3.8	80.3
Tunica	45.6	47.1	6.9	38.0	2.5	36.5	2.3	48.6
Washington	95.7	84.4	11.6	102.4	4.0	93.2	5.9	124.1
Yazoo	94.5	89.3	23.4	93.9	7.5	81.9	5.2	108.9

RICE:

County	Official	SYN	SD	BFE	SD	CRE	SD	RPCE
Bolivar	74.0	50.8	11.9	66.2	3.6	66.9	6.1	60.9
Coahoma	15.8	20.3	4.7	10.4	2.5	10.7	1.0	9.7
Humphreys	3.6	22.8	5.2	7.1	2.3	4.7	0.4	4.3
Leflore	16.6	30.7	7.1	19.4	3.6	17.3	1.6	15.8
Sharkey	5.0	18.0	4.1	7.8	1.7	6.5	0.6	5.9
Sunflower	36.0	51.1	12.0	37.8	3.5	36.7	3.4	33.4
Tallahatchie	9.6	20.9	5.1	8.5	3.0	8.1	0.7	7.4
Tunica	17.5	17.6	4.3	9.9	2.6	13.0	1.2	11.9
Washington	30.5	39.6	9.0	22.6	3.5	28.0	2.6	25.4

Table 3: Iowa Estimator Accuracy

	CORN				SOYBEANS			
EST	MD	RMSD	MAD	LAD	MD	RMSD	MAD	LAD
BFE	-0.6	6.8	5.4	14.3	-8.6	11.9	9.1	25.5
RPCE	9.6	12.6	10.6	17.9	-2.3	10.3	7.4	26.7
CRE	0.8	7.4	6.3	13.5	-8.0	13.5	9.0	33.4
SYN	16.2	23.8	17.6	53.3	-12.0	28.0	21.6	54.6

Table 4: Mississippi Estimator Accuracy

	COTTON				RICE			
EST	MD	RMSD	MAD	LAD	MD	RMSD	MAD	LAD
BFE	-1.8	10.0	7.8	20.7	-2.1	5.2	4.5	7.9
RPCE	13.2	17.2	13.7	31.8	-3.8	5.6	4.1	13.1
CRE	-7.2	12.5	10.2	26.1	-1.9	3.5	2.7	7.1
SYN	-1.8	19.4	13.2	46.5	7.0	13.9	12.2	23.2