A COMPARISON OF METHODS FOR ESTIMATING START-OF-SEASON FROM OPERATIONAL REMOTE SENSING PRODUCTS: FIRST RESULTS

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ABSTRACT

The start of the growing season is a valuable leading indicator for food security monitoring in the Sahelian region of West Africa. Unfortunately, such information is rarely available from ground sources in a timely manner. Operational remote sensing products including vegetation index and rainfall estimate images show promise for filling this gap. Three techniques for inferring start-of-season from the time series remote sensing data were the subject of a preliminary investigation. First results show systematic disagreement with ground reports, with a general tendency for late estimates. The systematic nature of the discrepancies suggests that new decision criteria can be devised that will result in better agreement with ground reports. Prospects for obtaining reliable operational monitoring products are encouraging.

INTRODUCTION

The Famine Early Warning System (FEWS) is a project of the U.S. Agency for International Development (USAID) that performs food security analysis for extensive areas of sub-Saharan Africa. Monitoring rainfed agriculture is an essential component of FEWS activities, especially where seasonal rains are highly variable in both space and time. A late start to the growing season can be one of the principal factors contributing to poor production of staple crops like millet, sorghum, and maize. Initial results of an investigation of alternative methods for estimating start-of-season (SOS) through processing and analysis of operational FEWS remote sensing products have been prepared.

BACKGROUND

USAID's FEWS is an information system designed to help decision makers prevent famine in sub-Saharan Africa. FEWS specialists in the U.S. and Africa assess crops and rangeland conditions for early indications of potential crop failures and as part of annual end of season vulnerability assessments. Ground information is gathered from available sources, but for many countries data are unavailable or of uncertain quality. Even for countries with the best data-gathering facilities, there are inaccessible parts of their territory where food security problems can go undetected using only the available ground data. For these reasons, FEWS relies heavily on remotely sensed data to supplement ground information (Hutchinson, 1991). The products presently used include 10-daily, or "dekadal" (World Meteorological Organization, 1992), Normalized Difference Vegetation Index (NDVI) images and automated rainfall estimates (RFE). Initial assessments made using remote sensing and ground truth are combined into a final assessment using a convergence of indicators methodology. The two remote sensing tools have proven effective in identifying problem areas, and users find it valuable to have the information from two independent satellite sources. However, most FEWS specialists are not trained in remote sensing and find the NDVI imagery to be easier to use than the RFE. In any case, derived products explicitly mapping a key agricultural variable, like SOS, are desirable because they more directly address the concerns of food security analysts.

The Sahelian region was selected ahead of other FEWS-monitored countries for our first investigation of remote sensing of SOS due to the technical expertise in agronomy, meteorology and remote sensing of FEWS field staff in West Africa. For this developmental stage, field comparisons could be made for Burkina Faso, Chad, Mali, Mauritania and Niger. Climatic zones for these countries are based on annual rainfall received and stretch across the region in bands that are roughly parallel to the equator. Temporal rainfall patterns (annual hyetographs) are unimodal. The Intertropical Convergence Zone (ITCZ) brings rain into the southern edges of the region starting in April. A maximum northerly extent of about 17 degrees North is reached in August, and then the ITCZ moves south, leaving the area by early October. For agricultural purposes, the climatic zones include the northern Sahelian zone (about 300-400 mm of rainfall per year), the Sudano-sahelian zone (400-800 mm per year) the Sudanian zone (800-1200 mm per year), and in the far south of Burkina Faso and Chad, the Sudano-guinean zone (>1200 mm rainfall per year).

The short and erratic nature of the rainy season has encouraged the adoption of pearl millet and sorghum as the main subsistence crops in these countries. The timing of the start of the rains is quite unpredictable. The timing of the end of the rains, however, is more dependable, and once the rains have stopped the ground dries out quickly and there is little further plant growth. Traditional varieties of millet and sorghum grown in this region have adapted to this pattern through photoperiod sensitivity, that is, daylength triggers flowering about a month before the rains end. For such varieties, an extension in the rains at the end of the season will have no impact on yield. By contrast, the start of season is critical since it determines the length of the growing period and, consequently, conditions expectations for the harvest.

After May 1, farmers in the region will generally plant their crops when there is one dekad of good rains, however, they will plant earlier if significant rainfall is sustained through two dekads. Failed sowings are common, and farmers reseed frequently throughout the season, up to a last useful date approximately seven dekads before the end of season. As crops are planted later and later in the season, they have a shorter and shorter time to produce leaves before flowering occurs at the critical daylength. Fewer leaves mean less photosynthesis and fewer carbohydrates produced for grain filling. Hence, later sowings inevitably lead to reductions in yield from the maximum possible. In some years, rainfall patterns are so unfavorable that no successful sowings occur before the last useful date, and farmers must plant low yielding short-cycle crops to ensure they will have something for their families to eat.

Because of the critical impact of SOS on food security in the Sahel, it is a valuable leading indicator for use by early warning systems. However, SOS information is rarely available from ground sources in a timely manner for all areas where there are potential food shortages. Remotely sensed data promise to fill this gap, and for this reason we have undertaken to develop and test techniques to estimate the start of the growing season from operational FEWS remote sensing products.

DATA SETS EMPLOYED

Remotely sensed estimates of rainfall in the form of RFE images have been produced for FEWS by NOAA's Climate Prediction Center since 1995 (Herman et al., 1997). The RFE are prepared on a 0.1-degree grid from thermal infrared images from Meteosat, the European geostationary satellite. Meteosat images, acquired every 30 minutes, are used to identify areas of cold cloud top temperatures (less than 235K). The duration of these temperatures over a dekad is used to make an initial estimate of convective rainfall. Then, dekadal rainfall totals from 760 stations that report electronically through the WMO Global Telecommunication System (GTS) are used to remove bias from the cold cloud estimates. Finally, areas of "warm cloud" rainfall, associated with orography, coastal areas, and frontal activity, are estimated from analysis fields of NOAA's operational Global Data Assimilation System (GDAS) (Kanamitsu, 1989). Fields of wind direction, relative humidity, and a digital elevation model are used to identify these areas of non-convective lifting and condensation. RFE images prepared in this way were used for estimation of SOS during 1998 and 1999. For the case of long term average dekadal rainfall, we utilized images derived from monthly grids produced by the Australian National University (ANU) (Hutchinson et al., 1996) through interpolation of ground station data. The nominal period of record for the ANU source station data is 1920-1980. For each pixel, simple linear interpolation of long term average monthly totals was performed to obtain long term average dekadal values.

GDAS analysis fields, generated every 6 hours, were used to estimate dekadal potential evapotranspiration (PET) on a spatial basis using the Penman-Monteith equation. Specifically, the formulation of Shuttleworth (1992) for reference crop evaporation was used. The spatial resolution of the fields is one degree, or about 100 km. Fields used included air temperature, atmospheric pressure at the surface, wind, relative humidity, and radiation (long wave and short wave, outgoing and incoming). Each day's potential evapotranspiration was computed, and appropriate sums were made to get dekadal totals. For the case of long term average PET, grids produced by the FAO Remote Sensing Center in Rome (Bernardi, personal communication) through interpolation of ground station data were used. The period of record for the PET data was 1961-1990.

The spatial variation of soil water holding capacity (WHC) was characterized using the FAO Digital Soil Map of the World (FAO, 1994). The scale of the original mapping is 1:5,000,000, and the soil polygons carry attributes which include an estimate of easily available water capacity in the upper 100 cm, based on soil physical characteristics. These are the values that were adopted for calculation of soil moisture conditions. The FAO soil map was rasterized to match the 0.1-degree RFE grid.

Vegetative surface conditions can be objectively evaluated using NDVI derived from Advanced Very High Resolution Radiometer (AVHRR) data. NDVI temporal profiles have been used to observe and analyze the phenological behavior of different broad vegetation types (Defries and Townshend, 1994; Reed et al, 1994). Smoothed NDVI data can improve seasonal vegetation characterization and determination of metrics, like SOS. The derivation of seasonal metrics is usually based on identification of trend changes in NDVI values. Reducing the number of spuriously low NDVI values caused by atmospheric contamination reduces the probability of identifying spurious starts of season.

The NDVI images used were those produced for FEWS operationally by the NASA/Global Inventory Monitoring and Modeling Studies (NASA/GIMMS) group (Los et al., 1994). These data are 10-day maximum-value composites in the Albers equal area projection, with a pixel resolution of 8 km. Processing techniques employed at NASA/GIMMS screen data for elimination of pixels with temperature less than 285 K (presence of clouds) and off-nadir viewing angle greater than 42 degrees. Channel 1 (red) and channel 2 (near infrared) radiances are normalized by Lambert cosine law to the case of solar zenith angle of zero, and NDVI is calculated using the resulting values according to the formula:

$$NDVI = (r_2 - r_1) / (r_1 + r_2) \qquad (1)$$

where r_1 and r_2 are the normalized radiances for channels 1 and 2. Correction for sensor degradation is applied to the NDVI values according to techniques described by Los (1993) that use ocean and desert targets as reflectance standards. The historical archive for these data covers the period 1982 – 1999.

Tabulations of SOS dates for ground locations in Niger were obtained by FEWS from the Direction de la Météorologie Nationale. The dates tabulated included SOS for 1998, 1999, and long term average conditions. A total of 111 stations were available with SOS dates for all three cases. These were used as "truth" for comparison with estimates derived from remotely sensed data.

METHODS OF ANALYSIS

Moisture Index Threshold

A common agrometeorological indicator used to estimate the beginning of the growing season is a simple supply/demand ratio, which we refer to as the Moisture Index:

$$MI = (P + S)/PET \qquad (2)$$

Where MI is the dimensionless Moisture Index, P is dekadal rainfall (mm), S is available soil moisture (mm), and PET is dekadal potential evapotranspiration (mm). For a station, an annual trace of the moisture index is inspected to identify the dekad when MI first exceeds 0.5 (Frère and Popov, 1986; Gommes et al., 1996). In order to calculate the dekadal MI on a spatial basis, the RFE images were used directly for P, as were PET grid values computed from the GDAS analysis fields. A simple bucket model was used to calculate a new value of S for each dekad, i, wherein:

$$S_i = S_{i-1} + P - PET \qquad (3)$$

subject to the constraint

$$0 \le S_i \le WHC \quad (4)$$

Moisture in excess of WHC is assumed to be lost as runoff or drainage out of the first 100 cm layer of soil. For the case of long term average conditions, 1998, and 1999, it was possible to compute a value of MI for each cell for each dekad. Available soil moisture was assumed equal to zero for the first dekad of January, a reasonable assumption given the prolonged dry season characteristic of the region.

It was found that a simple determination of the first dekad of the year in which MI was greater than 0.5 was inadequate for estimation of SOS. In many cases the MI would fluctuate just above and below 0.5 early in the growing season, making designation of the SOS dekad ambiguous. To remedy this, the requirement that the subsequent dekad have at least 10 mm of precipitation was added. This made the estimation of the SOS dekad more straightforward. These criteria were applied to the long term average, 1998, and 1999 data sets to get SOS grids for each case by the Moisture Index threshold method.

AGRHYMET Rainfall Accounting

The simplest method tested for estimating the planting dekad was that using the rainfall accounting approach of the Agriculture-Hydrology-Meteorology (AGRHYMET) Regional Center in Niger. Applying this method, SOS was identified by processing the RFE dekadal time series imagery for the growing season. On a per pixel basis, rainfall threshold criteria (AGRHYMET, 1996) were applied to the RFE values. Beginning several dekads in advance of the usual SOS, each pixel was tested to identify the first dekad in which at least 25 mm of rain fell. To test for failed plantings, the next two dekads' rainfall were required to total at least 20 mm. If they did not total 20 mm, testing for the SOS dekad resumed. The result was a grid, on the 0.1-degree spacing of the RFE, with each cell's value being the dekad number of its SOS. (The range from 1 through 36 defines a full year of dekads, from the beginning of January to the end of December, there being three dekads per month (WMO, 1992)). Grids of this kind were calculated for long term average, 1998, and 1999 rainfall time series.

Analysis of NDVI Time Series

NDVI data are typically very noisy, affected by cloud contamination, atmospheric perturbations, and variable illumination and viewing geometry, all of which tend to reduce the NDVI value (Los et al, 1994). A weighted least-squares linear regression approach to temporal NDVI smoothing was applied to reduce contamination in the NDVI signal (Swets et al. 1999). With this method, a moving window operating on the NDVI time series is used to calculate a family of regression lines associated with each point. The regression lines at each point are averaged, and interpolation between points provides a continuous temporal NDVI signal. Since the noise in the NDVI signal generally reduces the NDVI value, a weighting factor is applied to favor peak points during the growing season, to assure that all peak NDVI values are retained. The resulting smoothed curve has the favorable characteristic that it is statistically bound to the original raw data points.

To determine start-of-season, the approach developed by Reed et al. (1994) was utilized. This technique compares a delayed moving average (MA) of the smoothed NDVI signal to the original smoothed signal. The point at which the delayed MA intercepts a monotonically increasing NDVI signal is defined as SOS. The length of the MA window is adjustable, and generally depends upon the length of the non-growing season. For our study, the smoothing algorithm was based on a regression window of 5 data points, and the SOS algorithm was run with an MA window of 21 data points (i.e., 21 dekads, or 7 months). SOS was computed in this way for images for the 1998 and 1999 growing seasons, as well as the dekadal average images for the available 1982-1999 archive.

Tabular SOS data from the Direction de la Météorologie Nationale were linked to digital maps of the fourth level administrative units of Niger (USGS, 1996) using geographic information system software. This was done to facilitate comparison of SOS estimates with the ground reports.

RESULTS

Geographic information system software was used to compare SOS estimates with ground reports on a spatial basis. Fourth level administrative units (arrondissements) for Niger were used for this purpose. Remotely sensed estimates of SOS dekad were aggregated to the arrondissement level by calculating the median value of the pixels falling within it. In the case of ground reports, if more than one station fell within an arrondissement, the average SOS dekad was calculated, rounded to the nearest whole value. Results were tabulated in a contingency table, or confusion matrix. Cases of agreement are tallied along the diagonal, and appear in bold. Table 1 presents the contingency tables comparing estimated SOS for long term average conditions using (a) MI threshold, (b) AGRHYMET rainfall accounting, and (c) NDVI time series analysis. Cases off the diagonal on the lower left represent late estimates of SOS by remote sensing; estimates falling in the upper right half of the table are early compared to ground reports. Figure 1 presents the results cartographically. The contingency tables for the 1998 season are presented in table 2, and the corresponding images appear in figure 2. The contingency tables for the 1999 season are presented in table 3, and the corresponding images appear in figure 3.

DISCUSSION

Long Term Average SOS

None of the remote sensing estimates of long term average SOS matched very well with ground reports. The MI threshold and rainfall accounting methods both had fewer than 1% of their pixels on the diagonal of the contingency table, while the NDVI method was not much better with only 9% matching. However, the differences from ground reports seem to be fairly systematic, especially in the cases of the MI threshold and rainfall accounting methods. Remotely sensed estimates are for the most part late by one or two dekads. For example, if SOS estimates by the MI threshold method were systematically shifted to be two dekads earlier, 53% of pixels (1281 of 2400) would fall on the diagonal of the contingency table, and fully 97% of pixels would be within + /- 1 dekad of the ground reports. In the case of rainfall accounting, shifting all estimates to be one dekad earlier would put 62% of pixels on the diagonal, and 94% of them would be within +/- 1 dekad of ground reported SOS. SOS estimates from NDVI time series would likewise seem to improve through the application of a systematic shift to be earlier by one or two dekads, though there is far more scatter on the contingency table than for MI threshold and rainfall accounting methods. There are broad areas of incorrect early (April, May, June) starts in the northern part of the study area that complicate interpretation of the contingency table for the NDVI method. Over all three methods, the results suggest that adjustment of the specific criteria applied to the remotely sensed data to estimate SOS could yield significantly better results. For example, the 0.5 MI threshold might be lowered and/or the 10 mm contingency dropped; the 25 mm threshold and 20 mm contingency of the rainfall accounting method might be relaxed; and the delay period used to compare the NDVI time series with itself to detect signal upturn might be adjusted.

SOS for the 1998 and 1999 Growing Seasons

Results for the 1998 and 1999 growing seasons are interesting to compare because they are quite different in character. There is a fairly good spread among the ground reported SOS in 1998, while in 1999 there are very few starts before late June/early July (dekads 18 and 19). For both seasons, outright agreement with ground reports is quite limited for all remotely sensed estimates, but as in the case of long term average SOS, the discrepancies have a significant systematic component to them. This is more evident in 1999 than in 1998, where a one dekad shift in rainfall accounting and NDVI estimates of SOS would put them within +/- 1 dekad of ground reports in 92% and 93% of cases, respectively. The MI threshold method turns in the best result of all for the 1999 season, with 92% of estimates within +/- 1 dekad of ground reports without any shift applied. The results for 1998 show more scatter than 1999, and interpretation of them may be complicated by large areas in the north being assigned to ground reports of SOS in early June. These ground reports may be applied too widely, and should be checked.

Table 1. Contingency tables comparing ground reports of long term average SOS (columns) with remotely sensed estimates (rows): (a) MI threshold, (b) AGRHYMET rainfall accounting, and (c) NDVI time series analysis. Units are pixel counts.

LONG TERM AVERAGE

Reported SOS

(a)		12	13	14	15	16	17	18	19	20	21	22
	12											
	13											
	14											
	15											
SOS	16			11								
from	17			1	118							
MI	18				8	63	80					
	19				14	104	287	350	**24**			
	20					20	117	116	315	**14**		
	21						1	71	647			
	22									39		

Reported SOS

(b)		12	13	14	15	16	17	18	19	20	21	22
	12											
	13											
	14											
	15			11								
SOS	16			1	9							
from	17				109	43						
Rainfall	18				22	27	160	**14**				
	19					117	324	412	**166**	14		
	20						1	111	820			
	21									39		
	22											

Reported SOS

(c)		12	13	14	15	16	17	18	19	20	21	22
	12											
	13											
	14											
	15			11			1		608			
SOS	16			1	9			36	173			
from	17				7	85	**86**	208	18	39		
NDVI	18				124	1	110	**24**	24			
	19					50	95	48	**84**			
	20					51	182	195	79	**14**		
	21						11	26				
	22											

Figure 1. Long term average SOS in Niger by ground reports, by moisture index threshold, by AGRHYMET rainfall accounting, and from NDVI time series analysis. SOS dekad is color-coded according to the legend.

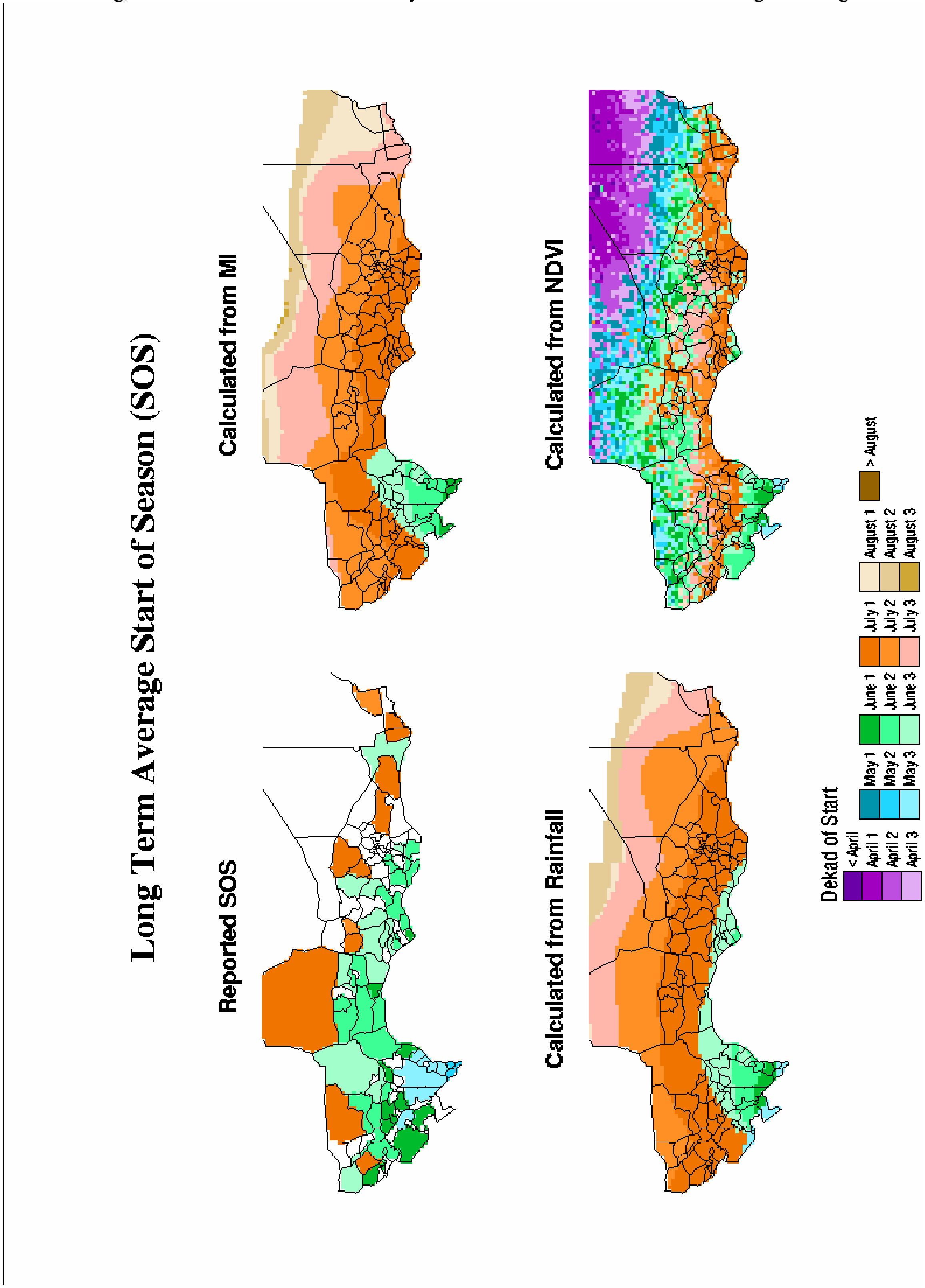


Table 2. Contingency tables comparing ground reports of 1998 SOS (columns) with remotely sensed estimates (rows): (a) MI threshold, (b) AGRHYMET rainfall accounting, and (c) NDVI time series analysis. Units are pixel counts.

1998 GROWING SEASON

Reported SOS

(a)		12	13	14	15	16	17	18	19	20	21	22
	12	**9**	14									
	13	13										
	14			**6**								
	15											
SOS	16	10	7	36		**77**						
from	17		118	54		11						
MI	18	23	14	65	99	260	75					
	19			3	39	189	20	57	**81**	60		
	20	50		11		126	52		26		36	
	21					609						
	22								39	71		**39**

Reported SOS

(b)		12	13	14	15	16	17	18	19	20	21	22
	12	**12**	14									
	13	17		6								
	14		68	**23**								
	15					57						
SOS	16	3	21	84	70	**88**	39					
from	17		50	1		11	**10**					
Rainfall	18	23		50	29	283	64		26			
	19				39	194	34	57	**81**	60	36	
	20	50		11		639						
	21											
	22								39	71		**39**

Reported SOS

(c)		12	13	14	15	16	17	18	19	20	21	22
	12											
	13											
	14	10	8									
	15	3	6			779					36	39
SOS	16	30	22	50		**1**	4			57		
from	17		68	15		127			18			
NDVI	18		28			264	39					
	19	20		45	39	53	30		**48**			
	20	42	7	51		25		57	73	**74**		
	21		14	14	99	23	74					
	22								7			

Figure 2. SOS for Niger in 1998 by ground reports, by moisture index threshold, by AGRHYMET rainfall accounting, and from NDVI time series analysis. SOS dekad is color-coded according to the legend.

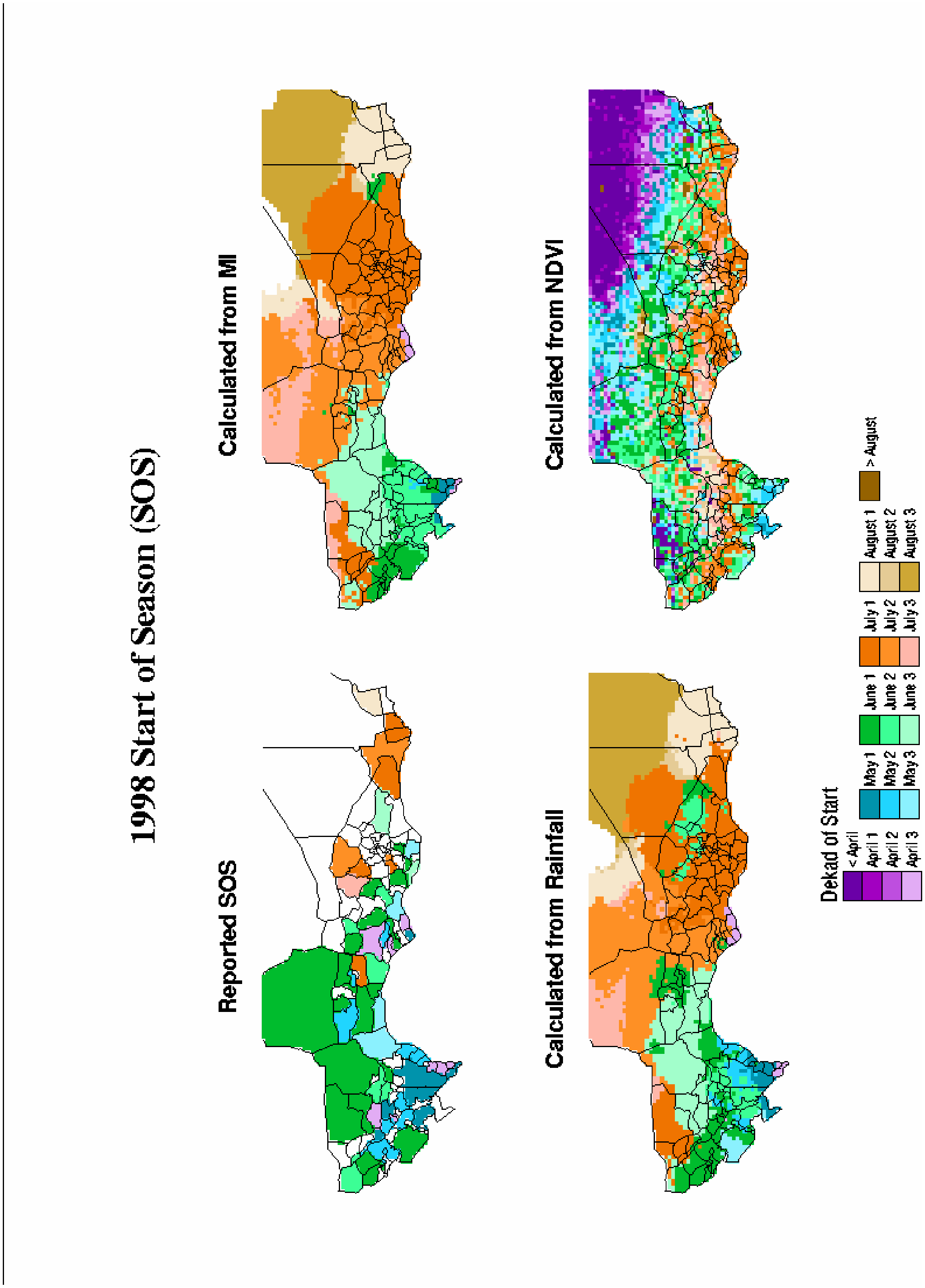


Table 3. Contingency tables comparing ground reports of 1999 SOS (columns) with remotely sensed estimates (rows): (a) MI threshold, (b) AGRHYMET rainfall accounting, and (c) NDVI time series analysis. Units are pixel counts.

1999 GROWING SEASON (through Sep. 20)

Reported SOS

(a)		12	13	14	15	16	17	18	19	20	21	22
	12					28		23				
	13											
	14											
	15						15					
SOS	16											
from	17											
MI	18			9	25	68		**114**				
	19							59				
	20			25				388	400	**215**	39	
	21							9	164	760		
	22							16	11			

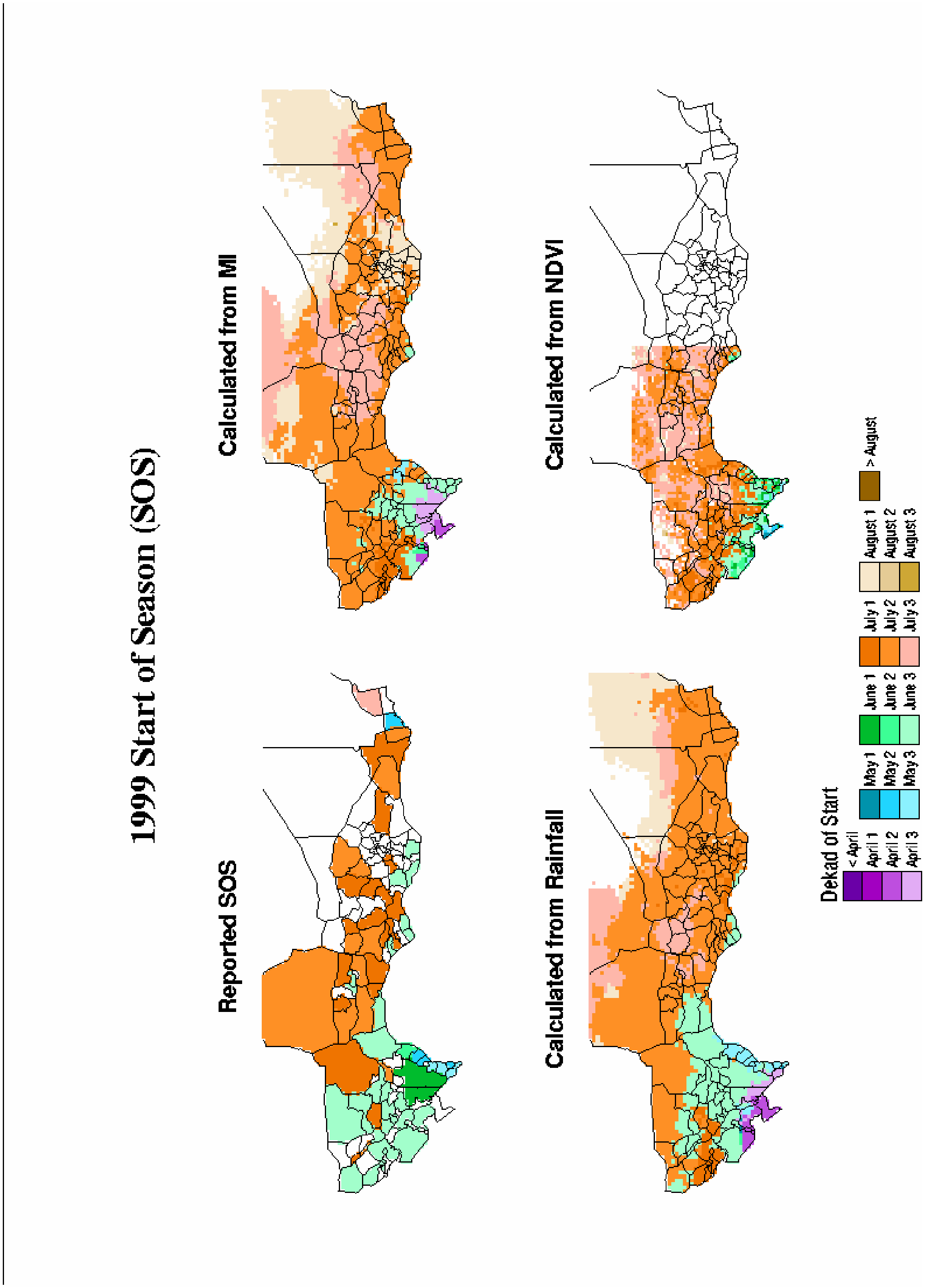
Reported SOS

(b)		12	13	14	15	16	17	18	19	20	21	22
	12				8	28		22				
	13							1				
	14											
	15			17	**17**		15	1				
SOS	16											
from	17											
Rainfall	18					68		**290**		68		
	19							106	**23**			
	20			17				189	538	**883**	39	
	21								14	24		
	22											

Reported SOS

(c)		12	13	14	15	16	17	18	19	20	21	22
	12											
	13											
	14											
	15			3								
SOS	16				8							
from	17				17			1				
NDVI	18			14				**101**				
	19					96		39	**1**			
	20						15	407	256	**1**		
	21							5	69	821		
	22											

Figure 3. SOS for Niger in 1999 by ground reports, by moisture index threshold, by AGRHYMET rainfall accounting, and from NDVI time series analysis. SOS dekad is color-coded according to the legend.



PRELIMINARY CONCLUSIONS AND PLANS FOR CONTINUED WORK

A preliminary conclusion is that estimates of SOS based on remote sensing systematically differ from ground reports and therefore might be improved by adjusting decision criteria applied to the data. The available ground reports from Niger will be used to explore possible changes. When additional SOS ground reports become available from other countries in the region, they can be used to check these new criteria.

A characteristic of the MI threshold method is that the soil moisture accounting scheme applies the full amount of PET to the bucket, which is rather unrealistic. This will be modified by addition of a simple drying function that takes advantage of soil texture attributes in the FAO digital soil map. Enhanced carryover of moisture by the soil from one dekad to the next might result in earlier satisfaction of SOS criteria, bringing results more in line with ground reports. The rainfall accounting method might be modified by lowering the threshold amount for the SOS dekad, and/or the amount of rainfall that must be received in subsequent dekads. The number of subsequent dekads to be checked might also be varied. The NDVI moving average and regression windows are adjustable, and changes in their values may yield improved results. A similar technique, known by the acronym VAST (Vegetated Area in Space and Time), developed by FEWS in recent years, will also be investigated. Ground reports and the manner in which they are assigned areas to represent will also be reviewed to determine if this procedure contributes to disagreement with estimates based on remote sensing. Because there are so many options for refinement of the techniques, prospects are good for identification of reliable methods for estimating SOS from remote sensing data.

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