Potential of Soil –Moisture-Estimating Technology for Monitoring Crop Yields and Assessing Drought Impacts- Case Studies In the United States

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Abstract— This study examines the potential of the soil moisture estimates generated by satellite based microwave sensors. Two case studies pertaining to the Nebraska and California states of the United States are presented. In Nebraska, using the 1995-2010 data, the soil moisture estimates were found to be significantly correlated (Coeff. of correlation = 0.56) with the yield of maize, the main crop of Nebraska. In California, using the 1997-2013 data, the soil moisture estimates were found to be strongly positively correlated with precipitation (Coeff. of corr. = 0.77), and the yields of walnuts (Coeff. of corr. = 0.61), oranges (Coeff. of corr. = 0.40), lemons (Coeff. of corr. = 0.32), almonds (Coeff. of corr. = 0.31) and pistachios (Coeff. of corr. = 0.15). The reliability of these relationships could be improved by confining the analysis to counties that have significant number of acres planted for respective crops. It is concluded that the soil moistures estimates is an important source of the data that can be used for improving crop models and for assessing agricultural drought impacts and thereby improving drought management.

Index Terms—drought, crop yields, microwave, soil moisture

I. INTRODUCTION

The world's urban population is growing rapidly due to various reasons. The rural-to-urban migration has become a cause of concern not only for developing countries but also for many developed countries [14, 20]. Children of farmers do not want to continue farming because agriculture is becoming less and less attractive. In many countries, famers even commit suicides apparently because they are unable to return the money they borrow for buying farming inputs (e.g., seeds, insecticides, fertilizers etc.) after their crops fail or do not yield enough, for example, due to natural calamities such as drought or floods [8]. How to make the rural life more sustainable is very pertinent question facing the world today.

In recent years, farming technologies have made significant strides. These technologies address various aspects of agriculture including those focused at optimizing crop yields with minimum input (so called precision farming), drought monitoring and managing in order to minimize economic losses, and soil moisture estimating for monitoring crop yields or drought conditions etc. In particular, satellites have played an important role in contributing to improving farming technologies by providing a better spatial and temporal

coverage of vegetation conditions and soil moisture conditions of agricultural lands.

The earth resources satellites, in the case of the passive systems, make use of the visible, the infrared, and the microwave regions of the electromagnetic spectrum. In the case of active systems, satellites transmit microwave energy to image the Earth's surface. Microwave energy has been found to be particularly useful for estimating the surface soil moisture. Realizing this fact, the active as well as passive microwave sensors have been used for estimating soil moisture across the globe [6, 9, 12, 19]. The soil moisture estimates, having a spatial resolution of about 25 km x 25 km, are available with the Technical University of Vienna through the European Space Agency. These satellite based estimates have an edge over the in-situ soil moisture data that are recorded at weather stations at a limited number of locations and have better spatial and temporal coverages. The in-situ soil moisture data available from weather stations do not possess a desired temporal or spatial resolution. Users often depend on the precipitation and the temperature data instead of the soil moisture data for monitoring drought conditions or crop yields [2].

The earth resources satellites provide various products one of which, the Normalized Difference Vegetation Index (NDVI), has been applied extensively across the globe for monitoring and predicting crop yields and droughts [3, 4, 17, 22]. While the NDVI data have been available for decades and therefore have been applied widely, the soil moisture data have been made available only recently and therefore have not been well tested or as widely used as the NDVI data.

This study examines the potential of the soil moistures estimates derived from satellite data for monitoring crop yields and the agricultural drought conditions and present case studies for Nebraska and California states of the United States. The following section presents the soil moisture data collecting and preprocessing followed by the detailed description of the case studies focused at monitoring or predicting crop yields in the case of Nebraska and assessing the impact of drought on agriculture in the case of California.

II. SOIL MOISTURE DATA PROCESSING

The soil moisture estimates derived from the active as well as passive microwave sensors were available in the NetCDF format. These estimates were available on a daily basis but were downloaded at a 5-day interval in order to reduce the processing time while maintaining temporal resolution adequate for examining crop conditions. The NetCDF files were later converted into raster images using the ArcMap/ArcGIS tools. Using the state's shapefile and the soil moisture raster images, the soil moisture estimates were averaged for Nebraska as well as for California at a 5-day interval and for multiple years using a zonal statistics tool. Figure 1 shows a sample of how the data were averaged using an ArcMap program.

Fig. 1. Estimating the average soil moisture using the ArcMap program.

In the case of Nebraska, the soil moisture estimates were downloaded for the cropping season (1st April through 30th September) while in the case of California, the data were downloaded for the entire year. The correlation analysis was performed between the soil moisture estimates and other variables in these two states as explained in the following sections, for monitoring maize yields in the case of Nebraska and for assessing the impact of drought on agriculture in the case of California.

III. CASE STUDY 1: PREDICTING MAIZE YIELD FOR NEBRASKA

Nebraska is an agricultural state and is located around the middle of the United States. Its main crops include maize (or corn) and soybean. Agriculture contributes billions of dollars annually to the Nebraska's economy. Predicting maize yields can help improve maize-marketing at a national or an international level. Record-breaking or higher than average temperatures tend to affect crop yields [1, 5]. Agricultural planners always look for an improved model for making better marketing decisions. Many of the crop yield models employ variables relating to basic parameters, such as temperature, precipitation, evapotranspiration, [15, 21] or even satellite-based NDVI data that have long been available to users. The soil moisture data, although directly related to crop yields, are typically not recorded at weather stations and, in addition, these data significantly vary in time and space. Satellite data provide better spatial and temporal coverages and therefore the satellite-data-based variables may prove to be an important variables to be considered for inclusion into the crop yield

models. With this background, the potential of the satellite-derived soil moisture estimates was assessed by examining the strength of the relationship between the soil moisture estimates and the maize yield in Nebraska.

The 1995-2010 data were used for the correlation analysis. For this period, the maize yield data were collected from the National Agricultural Statistics Service (NASS) of the United States Department of Agriculture (USDA) - www.nass.usda.gov. The maize yield data were then regressed against the weighted soil moisture estimates to examine the strength of the relationship (Figure 2) in order to determine their eligibility as a variable for predicting maize yields.

Fig. 2. Relating the maize yield with the estimated soil moisture.

The relationship between the maize yield and the soil moisture averaged over the period from April 5 to August 30 was examined. The data for a few dates were either not available or covered too little area in Nebraska and therefore were excluded from the analysis. The April-August period included pre-planting, germination, vegetative and reproductive phases of maize. The relationship, as shown in Fig. 2, was found to be non-linear. The coefficient of correlation, R, was 0.565 (i.e. $R^2 = 0.32$) meaning that this single variable alone could explain up to 32% of the variance in maize yields making it eligible for inclusion into the set of variables designed for developing a maize yield predicting model for Nebraska.

IV. CASE STUDY 2: ASSESSING THE DROUGHT IMPACT ON AGRICULTURE IN CALIFORNIA

California has been reeling under drought for the past few years [10, 11, 13, 16, 18]. Low precipitation has impacted irrigation and has ultimately affected the agricultural economy of California by lowering production of the foodgrain crops, fruits, and nuts [7]. Fig. 3 shows the declining trend in the annual average precipitation for California during 1997-2013. During this period, the satellite based soil moisture estimates averaged for California also demonstrated a similar declining trend (Fig. 4).

Fig. 3. Annual precipitation in California, 1997-2013

Fig. 4. The soil moisture estimates averaged for California, 1997-2013

The correlation analysis presented in this case study involved the data averaged for the entire California. The findings would be more reliable if a county-based analysis was conducted. The state level analysis had resulted in a reasonably higher and a positive value for the correlation coefficient between the satellite-based soil moisture estimates and the precipitation. In the case of a few yield-based variables the correlation coefficients were found to be negative because the crops included in this analysis were concentrated only to specific counties and not fairly distributed across the entire state causing spatial inconsistency between the correlating variables.

The satellite derived soil moisture estimates adequately reflected the precipitation trend in California as supported by a high value of the coefficient of correlation (0.77) between them. The state level analysis produced a positive value for the correlation coefficient between the soil moisture estimates and the almonds-yield and the oranges-yield.

Usually the temperature and the precipitation data are used for studying drought conditions. These data are collected at point locations and do not adequately represent the spatial soil moisture coverage as done by the satellite based microwave sensors. The soil moisture estimates derived from microwave sensors were examined and their relationships with the yield of the main agricultural crops of California (maize, cotton, rice and wheat), nuts (almonds, pistachios, walnuts) and fruits (oranges, berries, lemon) were studied in order to assess the impact of drought on agriculture in California.

Agricultural data for California (acres, yield, and production) were collected from the NASS.USDA website. Weather data (average temperature and precipitation) were collected from the National Climatic Data Center, and the soil moisture estimates as derived in previous sections were used for the period from 1997 to 2013. For the same range of years, the annual crop yields were extracted for selected crops, fruits, and nuts, which occupy significant acres in California. Once the datasets were complete, a correlation analysis was performed between the soil moisture estimates and other variables - annual temperature and precipitation, yields of major food crops (maize, cotton, rice, and wheat), and yields of fruits and nuts (shelled almonds, pistachios, walnut, oranges/tangerine, apples, grapes, raspberries, and strawberries) in order to assess the drought impact on agriculture in California.

A. Soil Moisture Estimates versus Temperature and Precipitation

The coefficient of correlation between the soil moisture estimates and the annual average temperature was -0.53 while the coefficient of correlation between the soil moisture estimates and the annual precipitation was 0.77. This finding indicates an expected relationship between the soil moisture and precipitation or temperature, making the satellite-based soil moisture estimates a reliable variable to explain the temperature and precipitation variations.

B. Soil Moisture Estimates versus Foodgrains Yields

Only in the case of the winter wheat yield, the coefficient of correlation was found to be positive (0.43); in case of other crops (cotton, rice, and wheat), the coefficients were negative indicating the need for a county-based analysis. The soil moisture estimates were averaged for the entire state while few crops were only concentrated in a few counties and were not planted reasonably uniformly across the state. This caused inconsistency in the spatial coverage between the correlating variables, which resulted in negative relationships.

C. Soil Moisture Estimates versus Yields of Fruits and Nuts

The data for nuts were only available since 2007. In the case of walnuts, the correlation coeff. was 0.61, followed by almonds (Coeff. of corr. = 0.31), and pistachios (Coeff. of corr. of 0.15). In the case of other fruit crops, the coefficient of correlation was negative barring lemons (Coeff. of corr. = 0.32) and different orange types (Coeff. of corr. about 0.40). The lemons and oranges data were available for the complete period (1997-2013).

V. CONCLUSIONS

In the case of Nebraska, the microwave based soil moisture estimates were found to be significantly correlated with the yield of maize, the main crop of Nebraska. In the case of California, the reasonably strong coeff. of correlation was

found between the soil moisture estimates and temperature, precipitation and yields of a few crops (walnuts, almonds, winter wheat, and oranges). The soil moisture data present a good source for improving maize yield prediction and for assessing agricultural drought conditions. By providing early warnings of agricultural drought based on predicting low crop yields, these estimates can significantly contribute to improving drought management, which in turn will contribute to sustaining the rural lives.

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