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Millet yield estimates in the Sahel using satellite derived soil moisture time series

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ABSTRACT

In the Sahel, crop growth and yield are strongly linked to climate fluctuations. The low and erratic rainfall the Sahel region has experienced for several years led to poor harvests, associated with dramatic food crises and famines. Consequently, numerous studies were conducted to develop innovative techniques to estimate crop yield based on satellite measurements. Unlike most approaches which use rainfall, temperature or vegetation indices to derive crop yield estimates, the present study investigates the potential of satellite-derived soil moisture products. This study focuses on millet, a major food crop in Africa. A first step was devoted to analyzing the relation between soil moisture and millet yield at the local scale using ground-based soil moisture and millet yield measurements obtained at ten site locations in Niger. Then, the statistical relationship obtained at the local scale was assessed at the regional scale (Niger, Mali, Senegal and Burkina Faso) using satellite-based soil moisture mapping (based on a simple land-surface model and a satellite precipitation product) and compared to millet yield estimates from the Food and Agriculture Organization (FAO) database. It was shown that millet yield variations are closely linked to soil moisture variations during two key periods of the plant growth: the "grain filling" and the "reproductive" periods. Soil moisture variations during these two periods led to explain 81% ($R^2 = 0.81$) of the FAO millet yield variations from 1998 to 2014 in the Sahel.

1. Introduction

Large-scale crop monitoring and yield estimation are essential for development and economic planning (Whitcraft et al., 2015). An accurate forecast of crop yield also helps reduce speculative behavior and thus limits food price volatility (Hoffman et al., 2015). Due to global warming, most of the developing world is expected to face increased risks from extreme climate events, such as droughts, flooding and heat waves (IPCC 2012, 2014), such that the present concerns on observed crop yield variability should further deepen. The threat posed by climate change to global food security translates into one of the most important challenges in the 21st century, which is to supply sufficient food for the increasing population while sustaining the already stressed environment.

Crop yield forecasting involves estimating crop yields (tons/ha) and production before the harvest actually takes place, typically a couple of months in advance. Crop forecasting systems primarily rely on satellite remote sensing. The most common algorithms use optical and near-infrared remote sensing to derive vegetation indices (VIs) that provide a global indicator of photosynthetic canopy cover or leaf area index (Sellers et al., 1992; Guan et al., 2015). The Normalized Difference Vegetation Index (NDVI) was one of the first VIs developed (Tucker, 1979) and has been widely used for operational crop monitoring (Maselli et al., 1992; Funk and Budde, 2009). Various methods to estimate crop yield were also proposed using thermal, solar-induced fluorescence and microwave measurements. Indeed, land-surface temperature measurements can be used to estimate evapotranspiration, which may be closely related to the plant water availability (Anderson et al., 2013; Khanal et al., 2017). Solar-induced fluorescence has been used as a proxy of plant photosynthesis (Guanter et al., 2014; Guan et al., 2016; Guan et al., 2017). Finally, microwave frequencies have been used to derive vegetation optical depth, which is mostly related to the vegetation water content and biomass change (Liu et al., 2011; Guan et al., 2014; Hosseini et al., 2015).

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Although numerous studies have shown good agreements between different VIs and crop yield (Bolton and Friedl, 2013; Mkhabela et al., 2011; Leroux et al., 2016), some studies pointed out the role of water stress conditions which can disrupt the relationship between vegetation greenness (or biomass) and crop yields (Ines et al., 2013). The influence of soil moisture content on crop growth should be significant, particularly in arid and semi-arid regions. However, only few studies investigated the potential of satellite-based soil moisture products to derive crop yield estimates. Some previous related works can be found in Bolten et al. (2010), Chakrabarti et al. (2014), Ines et al. (2013) or in reviews related to the use of satellite remote sensing for agricultural applications: Steele-Dunne et al. (2017) and Wagner et al. (2013).

In this study, we propose a methodology to investigate the potential links between soil moisture variations and millet crop yield in the Sahel region. The study is based on a large amount of millet yield measurements obtained over 10 villages in the Niamey region (Niger) from 2004 to 2012, and millet yield estimates at the country scale (Niger, Mali, Senegal and Burkina Faso) from 1998 to 2014 provided by the Food and Agriculture Organization (FAO). In parallel, soil moisture measurements are provided by the AMMA-CATCH Observatory, and by an existing model and satellite-based soil moisture product. The first part of the paper investigates potential statistical links at the local scale. In a second step, the statistical relationships found at the local scale are applied to the regional scale.

2. Data & methods

2.1. Study Area

The Sahel is the ecoclimatic zone of transition in Africa between the Sahara to the north and the Sudanian Savanna to the south. The Sahelian climate is characterized by mean annual precipitations between around 200 and 600 mm which are driven by the West African monsoon with an annual mono-modality generating a dry and a wet-season, the latter occurring from June to October. With an annual mean temperature of 29° C, the Sahel is known as one of the hottest places on earth. Due to the reliance on rainfed agriculture (less than 2% of irrigated area), the precipitation variability (spatial and temporal) strongly impacts agricultural crop production. The millet production, mainly located in Niger (Fig. 1), is one of the main important food across the Sahel region of Africa and is Niger's principal rainfed subsistence crop (~47% of the total production).

The area around Niamey was extensively instrumented during the AMMA (African Monsoon Multidisciplinary Analysis) scientific experiment (Redelsperger et al., 2006; Lebel et al., 2009). Numerous hydrological, meteorological and biological measurements were installed in 2005 and are now carried out by the AMMA-CATCH Observatory. In addition, crop yield measurements were obtained at various locations in collaboration with CIRAD (Centre de coopération Internationale en Recherche Agronomique pour le Développement) and AGRHYMET Regional Center in Niamey.

2.2. Millet crop yield

Two different millet crop datasets were used in this study. The first dataset is composed of millet crop yield and production measurements obtained in ten villages around Niamey (Fig. 1b). The protocol was to monitor about thirty agricultural parcels for each village from 2004 to 2012 (total of more than 300 parcels each year). For each parcel, three randomly located subplots (~5 m x 5 m) were surveyed by weighing millet grain production at harvest time. Grain weight was then normalized by the surface of the subplots to obtain the average plot yield in kg/ha. A detailed description of the dataset can be found in Marteau et al. (2011). This dataset was analyzed from 2006 to 2012 in connection with the availability of soil moisture data (next section). Fig. 2 shows the evolution of the millet yield from 2004 to 2012 measured on the ten villages. The averaged (10 villages) annual values are presented with bars and the overall mean annual value is 680 kg/ha. This value is common in Niger (maximum of 1250 kg/ha, Rockstrom et al. (1999) and generally less than 1000 kg/ha, http://www.jaicaf.or.jp/publications/niger_f.pdf) due to the quasi absence of inputs, fertilizers, and irrigation.

The second dataset is provided by the Food and Agriculture Organization of the United Nations Statistical division (FAOSTAT) which collects international information from nearly every country. The dataset is based on annual surveys submitted by governments and contain statistics on area and production harvested for dry grain only. The spatial distribution of the millet production areas in the Sahel is illustrated in Fig. 1. This map results from the merging of several land cover datasets: (i) the GLC2000 land cover, (ii) a global land cover compiled by IFPRI based on the Global Land Cover Characteristics (GLCC) Database and (iii) an additional layer from the Forest Resources Assessment from the FAO. In this study, millet production statistics over Niger, Mali, Senegal and Burkina Faso will be used and are shown in Fig. 3.

2.3. Soil moisture dataset

2.3.1. In situ soil moisture measurements

Ground level soil moisture measurements are provided by the AMMA-CATCH Observatory. Soil water content is obtained using Campbell CS616 probes which measures the propagation duration of a high frequency signal through a wave guide (stainless rods) pitched in the soil. The dielectric constant variation due to the presence of water (or not) impacts the time propagation (in μs) which, after calibration and regression, provides a soil moisture estimation (in m^3/m^3). 18 sensors located in the Niger site of the AMMA-CATCH Observatory were used in this study to monitor soil moisture from near surface (5 cm, 6

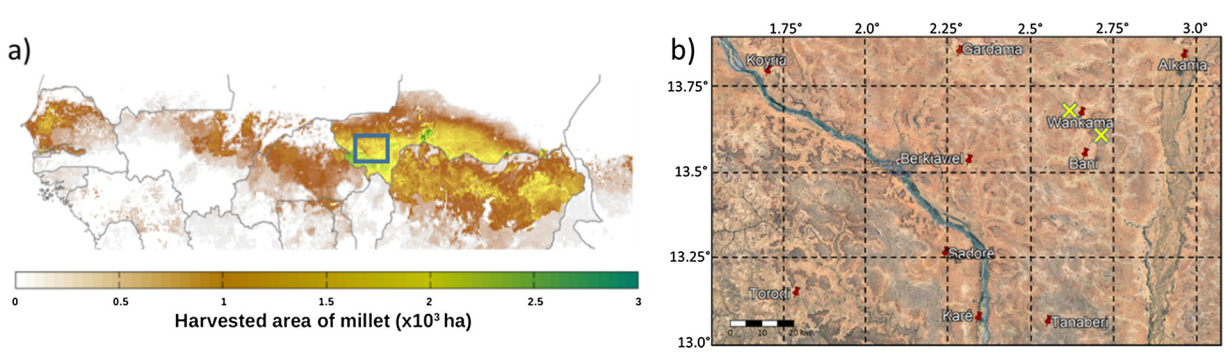

Fig. 1. a) Millet production areas in the Sahel (source: FAO Global Agro-Ecological Zone (GAEZ)). b) Location of the 10 villages in South-Western Niger where millet yield measurements are obtained, and soil moisture sensor locations in the Wankama region (yellow crosses). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)