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Estimating maize and cotton yield in southeastern Turkey with integrated use of satellite images, meteorological data and digital photographs

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ABSTRACT

This study focuses on yield estimates of planted areas of cotton and maize in southeastern Turkey. It integrates multi-temporal satellite images, daily digital photographs of cultivated parcels, and daily meteorological data. Our research produced vegetation cover fraction (VF) estimates from digital photos and defined relationships between this information and the spectral vegetation index (VI) obtained from satellite images. Meteorological parameters limiting the light use efficiency of crops (LUE), such as temperature and vapor pressure deficit, were also calculated and incorporated into the yield estimation process. Results showed that the use of digital photo-based VF rather than the fraction of photosynthetically active radiation (fAPAR) in the LUE model provided the most accurate yield estimates. It produced less than 5 percent relative error in cotton and maize test parcels. In general, the VF–SVI relationship showed high linear correlation, with a range of 0.825–0.980 R^2 in all test parcels. Crop specific regression equations derived from these relationships enabled yield estimates at the parcel level across the study area. When compared to statistical yield information at four districts, the remote sensing-based method proved to be reliable, with relative errors below 10 percent in most cases. Moreover, greenness index (GI) was also used in gross primary production (GPP) approximation, and yield estimates using this method also provided reasonable accuracy. Results also provided valuable information about the effects of region-specific meteorological conditions and crop management activities on yields. Finally, the higher yield estimation errors that result from the use of generic SVI–fAPAR equations in the literature indicate the need for local calibration of this relationship.

1. Introduction

Timely and accurate estimates of crop yield from local to regional scales is of paramount importance for societal, economic, agricultural, and policy considerations (Lobell et al., 2003; Fang et al., 2011). For example, regional-scale yield estimates enable potential agricultural production capacity to be predicted so that food pricing and stock management can be planned for the coming year. Yield estimates also add valuable data to modeling of agriculture–ecosystem relationships related to carbon cycling and climate change (Cassman and Wood, 2005). Using allometric relationships, crop yields can be converted to terrestrial net primary productivity (NPP) to be used to determine carbon budgets (Reeves et al., 2004; Ozdogan, 2011).

One form of agro-meteorological yield model is based on the approach introduced by Monteith (1972) that defines the relationship between light use efficiency (LUE) and biomass production. This approach makes use of observations of the fraction of absorbed photosynthetically active radiation (fAPAR) at different crop phenological development stages. It converts the amount of usable energy intercepted by the vegetation canopy to crop-specific biomass production. The LUE approach also lends itself nicely to satellite-based estimates of NPP (or its yield equivalent) because light absorption by plants is the primary driver of net carbon uptake and can be directly measured over large areas using remote sensing (Field et al., 1995).

Satellite images provide valuable information for large areas and possess temporal data collection capability. They have been widely used in crop yield assessment in a variety of environments (Baez-Gonzalez et al., 2002; Bastiaanssen and Ali, 2003; Doraiswamy et al.,

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2003; Gitelson et al., 2012). Since the spectral reflectance of plants has a high correlation with the vegetative status of various crops, research has revealed a significant relationship between spectral vegetation indices (VI) and crop yield (Groten, 1993; Wiegand et al., 1991). More specifically, it has been well documented that VI's are sensitive to vegetation changes in terms of physiological development and thus they have been used as indicators for crop cover fraction (VF), leaf area index (LAI) and fraction of absorbed photosynthetically active radiation (fAPAR) (Asrar et al., 1984; Liu et al., 2012; Myneni et al., 1995; Wang et al., 2001). The two most widely used VI's are the Normalized Difference Vegetation Index (NDVI) and Simple Ratio (SR), both of which display various degrees of correlation with vegetation biophysical properties (Gallo et al., 1993; Elmore et al., 2010; Serrano et al., 2000). For example, Wiegand et al. (1991) investigated a number of VI–fAPAR relationships using NDVI, SR, the perpendicular vegetation index (PVI), and the transformed soil adjusted vegetation index (TSAVI). Results of yield estimates were found to be significant and similar with all VI's tested. On the other hand, Gitelson et al. (2003) proposed a green index (GI) for LAI estimation in maize fields. It was reported to overcome the limitations of more traditional VI's that utilize the red wavelength. The improvement was attributed to the GI's ability to maintain correlation with LAI, even for large LAI values. It also held true during the tasselling stage of maize while the other VI's showed reduction in sensitivity to LAI due to large absorption of red light.

Although satellite remote sensing has the advantage of providing spatial data over large areas, work to date using these images with spatial resolution sufficient for parcel-based analyses has been fraught with temporal resolution constraints, since daily to weekly observations are required to capture rapid changes in crop development. For example, Lobell et al. (2003) pointed out the need for a predetermined time profile of fAPAR with field studies to calibrate VI–VF relationships. They combined their field-based canopy measurements at specific dates with SR and NDVI images using the linear functions presented by Sellers et al. (1996) and Los et al. (2000). They used linear interpolation to extend the canopy cover measurements to obtain daily information and single date VI analysis in order to estimate yield spatially. In this regard, the temporal resolution constraints of medium spatial resolution (10–100 meters) satellite images points to the need for ground-based observations to calibrate and validate the relationships between VI's and crop biophysical properties. However, field observations, often conducted at a specific point are insufficient to extend yield analysis to large areas (Menzel, 2002). Moreover, since agro-meteorological yield models require daily data about a crop's physical progress, standard in situ biophysical measurements could become quite difficult and cost prohibitive (Graham et al., 2009).

One way that is increasing in popularity to supplement labor-intensive field observations of vegetation progress is to use ground-based digital cameras for agronomic analyses. For example, Graham et al. (2009) investigated the suitability of digital cameras to observe plant phenology and used a color thresholding method to determine leaf development stages for a deciduous shrub. This study also raised the possibility of using ground-based cameras as a good source of reference data for satellite analysis. Further work by Laliberte et al. (2007) used object-based segmentation to determine vegetation cover. They used ground-based photographs and showed a high correlation between estimated and observed vegetation cover in mixed grassland areas. Li et al. (2010) also presented a method to analyze digital photographs to determine VF in wheat fields with different growth habits by applying the soil adjusted version of the green vegetation index proposed by Gitelson et al. (2002). Their results showed that there is a high correlation among VF extracted from digital photographs and LAI, above ground biomass. Pan et al. (2007) also used camera images to estimate VF in various wheat cultivars and reported high correlation between VF and LAI at four stages of crop growth. More recently, Sakamoto et al. (2012) performed detailed research for crop growth monitoring by using digital cameras that had both visible and near-infrared capabilities. They compared VI derived from digital cameras with those from the SKYE sensor and MODIS satellite images throughout the growing period in maize and soybean fields and found strong linear relationships between Camera-SKYE, Camera-MODIS and SKYE-MODIS VI datasets with R^2 values higher than 0.80.

With these developments in mind, the purpose of our research was to construct an agro-meteorological yield model for cotton and maize fields in southeastern Turkey, using digital photographs, multi-temporal satellite data and meteorological measurements. More specifically, we investigated the utility of digital camera-based VF measurements rather than fAPAR, and developed a LUE-based yield model over test parcels. We also defined a regression-based relationship between VF and VI's derived from multitemporal satellite images in order to obtain spatial fAPAR information. We then extended our findings to regional yield estimates at the parcel level with the use of multitemporal satellite images coupled with locally optimized meteorological data. Finally, we tested the use of Green Index of Gitelson et al. (2012) and the generic VI–fAPAR equation as approximations of gross primary production (GPP) in addition to our VI–VF approach and compared yield estimation results across these different approaches.

2. Study area

The study area covers a 60 km × 120 km segment of the Sanliurfa province, located in southeastern Turkey (Fig. 1). Sanliurfa is one of the largest provinces, with important contributions to national agricultural production, including 35% of the cotton, 8% of the wheat, 55% of pistachios and considerable amounts of maize, lentil and chickpeas. The region shows typical Mediterranean climatic properties, and receives most of the annual rainfall in winter, late fall and spring (average 510 mm). With the availability of irrigation, the climatic conditions of the province permit at least two growing seasons per year. The dominant crops in the early season are winter wheat and barley, while for the late season they are cotton and maize.

Cotton planting begins in early May and its harvest generally occurs from late September to mid-October. For maize, the ideal sowing period is late April to mid-May, but when it is the second crop of the season, late planting is common until the end of June. Harvesting is in late October over 10–15 days, depending on the shift in sowing time.

3. Data and methodology

3.1. Description of the test plots

In the test plots where the yield model was constructed, sowing of cotton was generally performed by a seed drill with 70–80 cm row intervals and seeds planted 15–20 cm apart in the rows; average seed dispersal rate is 15–25 kg ha^{-1}. Main cotton cultivars included Stoneville-453, Suregrow-125, BA-119, Carmen, DPL-388, and DPL-511. The common characteristics of these cultivars include mid- to early-maturation and medium plant height with similar seed and boll weights. For grain maize, planting was done with a seed drill, with 70 cm between rows and the seeds 25 cm apart. Average seed sown was 20–30 kg ha^{-1}. Hybrid cultivars, part of the FAO 700 and 800 groups, were selected for their late maturing properties when maize was planted as the first crop, while the FAO 600 group of mid- to late-maturing cultivars were preferred if it was