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Mapping field-scale yield gaps for maize: An example from Bangladesh

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ABSTRACT

Accurate estimation of the size and spatial distribution of the yield gap has many practical applications, including relevance to precision agriculture and technology targeting. The objectives of this study were to illustrate a methodology to create a yield gap map and to discuss its potential uses to provide optimal crop management recommendations to the farmers. We used the HybridMaize crop simulation model to estimate potential yield for maize grown in the winter season in northwestern Bangladesh. This is a high yielding environment, where farmers achieve yields as high as 12 Mg/ha. The model predicted a mean potential yield of 12.87 Mg/ha. We used a RapidEye satellite image acquired around tasseling to identify the maize fields, calculate ground cover and its regression to actual yield from farmers' fields. Next, the regression was applied to all the maize pixels in the image to calculate actual yield. In the last step, we created a yield gap map based on the difference between potential and actual yield. Yield gap maps will enable agronomists to identify production constraints on farmers' fields with large yield gaps. Alternatively, by learning from the farmers with the highest actual yields and analyzing their data, it will be possible to generate region or field specific, optimized crop management recommendations.

1. Introduction

Knowledge of the size of the gap between the potential and actual yield has various applications. They range from tailoring agricultural policies aiming at improving the livelihood of resource-constrained farmers to prioritizing research and extension work. Information on the spatial variability of the yield gap will also support the development of region, field or site specific recommendations, including 'real time' adjustments to management practices in response to weather events that change yield potential in a given season. There are various methodologies to estimate potential and actual yield, which then allow for a calculation of the gap between the two (Van Ittersum et al., 2013). One way to estimate potential yield is to conduct field experiments under well-managed, controlled conditions to restrict any limitations to yield. In such experiments, potential yield of any crop variety should not be limited by factors other than climate. However, it is a challenging task to omit any factor that limits and reduces growth and yield under field conditions. An alternative method is to use process based crop simulation models. Some of them have been calibrated and validated for a wide range of environments (Bouman and van Laar, 2006; Timsina and Humphreys, 2006). Their main strength is that they can take into account varying weather conditions among years and interactions with the environment and management, and thus are able to quantify the magnitude and variability of the potential yield. Moreover, they can also be used to assess whether a given year for which the actual yield data are available is representative or not. Data on actual yield are typically based on crop statistics. Formal and informal surveys, trade statistics as well as expert opinions are used for its estimation. Crop statistics are generally summarized and aggregated at various levels of administrative districts. These are political boundaries, and generally they do not delineate agro-ecological zones. Hence, there might be large differences in the yield gaps within an administrative district and they may not be representative for an agro-ecological zone or a field within that district.

In this paper, we are describing a method that makes use of remote sensing and crop modeling to predict the magnitude of the yield gap for maize at the field level. The case study with maize is set in northwestern Bangladesh. Maize has great potential in that country. Total area of maize production in 2010 was 152,000 ha with an average yield of 5.8 Mg/ha (FAOSTAT; http://faostat3.fao.org; verified October 31, 2012). When grown in the winter months (Rabi season), maize yields of up to 12 Mg/ha have been reported (Ali et al., 2008). Such high yields can be achieved with

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Abbreviations: HI, harvest index; LAI, leaf area index; MSE, mean squared error; NDVI, normalized difference vegetation index; PAR, photosynthetically active radiation; PVI, perpendicular vegetation index; WDVI, weighted difference vegetation index.

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4–5 irrigations, which is about 1/10 of the irrigation water requirements of ponded rice grown in the same region and season. Knowledge of the yield gap will serve to set up demonstration trials at key locations and to improve management recommendations. Hence, the objectives of this study are to illustrate a methodology to create a yield gap map and to discuss its potential uses to provide optimal crop management recommendations to the farmers.

2. Theory

In order to estimate actual yield of maize for an entire region, we are using remote sensing derived ground cover as an estimate of the light intercepted by the crop, which in return tends to be closely related to yield.

2.1. Estimation of ground cover with remote sensing

Optical sensors on satellites that are used for earth observation measure the amount of light reflected from the earth's surface. Reflectance from the bare soil usually steadily increases with wavelength. Plants, however exhibit a rather distinctive reflective pattern between wavelengths in the visible and near infrared spectrum. Healthy, unstressed plants use most of the light in the visible spectrum for photosynthesis and reflect only a small portion of it. However, in the near infrared spectrum, most of the light is scattered back from the interfaces of cell walls and intercellular air spaces (Slaton et al., 2001). These distinctive properties are being used in most algorithms that aim at estimating ground cover (GC), leaf area index (LAI) and other canopy properties such as chlorophyll content from remote sensing. The most commonly used vegetation index is the normalized difference vegetation index (NDVI). However, it tends to be strongly influenced by soil background conditions and to saturate when LAI exceeds 2. Huete (1987) demonstrated the strong influence of soil background on vegetation indices. The perpendicular vegetation index (PVI) developed by Richardson and Wiegand (1977) seeks to limit the effects of differences in soil moisture content on the index. The mathematically related weighted difference vegetation index (WDVI) described by Clevers (1989) assumes that the soil line runs through the origin.

The capability of WDVI to predict ground cover was widely tested in the 1980s and early 1990s in the Netherlands (Bouman et al., 1992). They found linear relationships between ground cover and WDVI throughout the growing season for potato, sugar beet, barley, wheat and oats. They reported that the average estimation accuracy of ground cover from WDVI was of the same magnitude as that of conventional methods, i.e., about 5% (absolute value) in most cases.

Most methods to predict ground cover require remote sensing data that have been calibrated to reflectance because they are making use of the soil line. However, Maas and Rajan (2008) described an elegant way to calculate ground cover based on digital numbers (DN), i.e., uncalibrated imagery. That approach is based on a visual analysis of the so-called tasseled cap. This is a plot of the DNs of the red (x-axis) versus those of the NIR (y-axis) band. That plot exhibits the two key features needed to calculate ground cover: the full canopy point and the soil line. At the full canopy point, the ground cover approximates 100%. This approach works well in regions with a diverse cropping pattern, where some fields have reached a full canopy, whereas other ones have bare soil.

2.2. The relation between ground cover and yield

Per definition, ground cover is the percentage ground covered by green leaves when seen from above. It is therefore a measure of the amount of light or photosynthetically active radiation (PAR) that is intercepted by a plant canopy. Monteith and Moss (1977) showed that cumulative light interception throughout a season is closely related to biomass production. In line with their findings, several studies demonstrated that cumulative intercepted PAR derived from remote sensing can be used to accurately estimate above ground biomass (Casanova et al., 1998; Christensen and Goudriaan, 1993). However, in order to estimate cumulative intercepted radiation, several satellite images as well as the date of crop emergence and maturity for each field are required. This approach is not very practical for a country like Bangladesh, where skies tend to be hazy during the winter months and typical field sizes are less than 1 ha.

The LAI, and thus ground cover of maize reaches its peak just before tasseling. It then declines at a slow and steady rate (Odenweller and Johnson, 1984). Hence, there is a period of several weeks around tasseling during which LAI does not change much. This offers a rather long window for the estimation of LAI. In maize, it has been shown that the amount of light intercepted around the silking phase is a key determinant of grain set (D'Andrea et al., 2008; Kiniry and Knievel, 1995; Lizaso et al., 2001). Hence, even if there are differences in sowing date among maize fields in a given region, an image taken around the time when the majority of the fields has reached tasseling or soon thereafter, can potentially serve as good indicator of the spatial variability of yield. However, the slope and intercept of the relation between ground cover and yield changes from year to year, since temperature and solar radiation have a strong impact on grain filling. It is therefore necessary to calibrate that equation.

3. Materials and methods

3.1. Study area

The study was conducted in the Rangpur district, in northwestern Bangladesh. That area is intensively cropped with rice during the rainy season. Winter (Boro) rice, potato, wheat and increasingly maize, as well as lentils, mustard, jute and other crops are grown during the remainder of the year under irrigated as well as rainfed conditions.

3.2. General crop production practices for maize

Maize in Rangpur is most commonly grown in the following cropping patterns: maize–fallow–transplanted monsoon (T. Aman) rice, potato–maize/relay maize–T. Aman rice, maize–relay jute/jute–T. Aman rice, or maize–pre monsoon (Aus) rice–T. Aman rice. In most of the areas, however, T. Aman–maize–fallow and T. Aman–potato–maize are the predominant cropping patterns. In T. Aman–maize–fallow system, maize is generally planted during November and December (called Rabi maize) and harvested during April and May, thus the growth duration of Rabi maize is around 150 days. In the T. Aman–potato–maize system, maize is sown as a relay crop 20–35 days after planting potato in January or it is grown after the early harvest of potato in late February to early March (called Kharif-1 maize), thus the growth duration of kharif-1 maize is around 110–115 days. The long duration, and hence the late variety of Rabi maize results in delay in planting of main Kharif season rice resulting in reduced rice yield while delay in harvesting of kharif-1 maize results in crop damage and poor grain quality due to storm and heavy rainfall at crop maturity (Ali et al., 2008; Timsina et al., 2011). Short duration hybrids are required in NW Bangladesh to intensify the cropping systems but they must have high yield potential too.

Most maize in Rangpur is grown on deep fertile alluvial soils supplemented by large amounts of NPK fertilizer. Maize farmers