Remote Sensing

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1 Introduction

There are three basic types of information required for PA:

- information on seasonally stable conditions, i.e, those that are relatively constant through the crop growing season, such as yield-based or soil-based management units, and only need to be determined preseason and simply updated, when and if necessary.
- information on seasonally variable conditions, i.e, those that change continually within the season, such as soil moisture, weed or insect infestations, and crop disease, and need to be determined numerous times during the season for proper management.
- information required to diagnose the cause of the crop yield variability and develop a management strategy.
- in nearly every application of PA and in every agro-meteorological model, knowledge of spatial variations in meteorological conditions is crucial. Multispectral images of coarse spatial resolution and fine temporal resolution should be used to produce local or regional maps of meteorological parameters such as insolation, PAR, rainfall, and others.

There are to approach to meet the information requirements of PA:

- tractor based sensors which control variable rate applicators in near-real time
- satellite, airborne or uav spectral observations

Tractor-based sensors

Several such sensors have been developed for measuring:

- soil organic matter (Tyler, 1994)
- soil nitrate levels (Adsett and Zoerb, 1991)
- soil clay content and thickness (Sudduth et al., 1995).
- weed sensors to discriminate weeds from standing crops (Thompson et al., 1990; Gu-yer et al., 1993)
- a tractor-based charged couple device (CCD) camera to discriminate plants from soil and trash for guiding most-beneficial chemical applications (Cai and Palmer, 1994)
- a sensor for assessing crop nitrogen status based on an in-field reference of known nitro-gen status (Blackmer et al., 1996).
- a fluorescence technique that allowed discrimination of residue from bare soil, and a commercial prototype that could be mounted on a trailer (Daughtry et al. 1995)

Satellite, airborne or uav spectral observations

Spectral observed imnages are usually transformed pixel by pixel according to certain vegetation indexes, which are more suitable for the analysis of crop and soil conditions.

- Normalized Difference Vegetation Index (NDVI)
- Normalized Difference Vegetation Index – Green (NDVI-green)
- Soil Adjusted Vegetation Index (SAVI)
- Photosynthetic Vigor Ratio (PVR)
- Plant Pigment Ratio (PPR)

2 Mapping Seasonally Stable Conditions

Grain Yield Monitor

Yield maps collected for several growing seasons can provide an integrated expression of relative productivity that is a property of the field and unchanging from year-to-year and from crop-to-crop. Yield maps have been used directly for management of:

- fertilizer application (Schueller and Bae, 1987; Eliason et al., 1995),
- water application (King et al., 1995)
- planting and soil engaging operations (Schueller, 1988)
- have important indirect applications in management of weeds, insects, and crop diseases.

Conventional Approach

The production of grain yield maps generally requires that instantaneous grain yields acquired at coarse and/or variant resolutions with DGPS positioning be interpolated to obtain average yields at a given, finer resolution. Generally, geostatistical analysis is used for this interpolation, based on kriging or the simpler inverse distance technique (Murphy et al., 1995). Long et al. (1995) compared four methods for deriving yield maps from combine-based yield measurements:

- interpreting soil survey maps
- interpreting aerial photographs (transformed to NDVI?)
- two kriging-based methods.

Multispectral images

Most studies suggest that NDVI can be effective for providing information on germination and vegetative stages, but this information must be combined with input from an agrometeorological model to accurately determine crop yields (Patel et al., 1991; Rudorff and Batista, 1991).

Soil Fertility Properties

Nielsen et al. (1995) identified several of the most important soil fertility attributes that could be mapped and managed for improved yield: available soil nitrogen or some other macro or micro plant nutrient, relative position and slope of the terrain, soil organic matter content. Maps of soil fertility and physical attributes are being used in PA to determine the responsive and nonresponsive parts of fields (Wolkowski and Wollenhaupt, 1995):

- Soil organic matter content has been directly related to the efficacy and rate of fertilizer applications
- Soil physical properties or landscape may be even more important than soil fertility in explaining yield variations

Conventional Approach

Bell et al. (1995) outlined three approaches for mapping soil variability for PA:

- county soil surveys at 1:12,000 to 1:24,000 scales
- geostatistical interpolation techniques (e.g., kriging) to map soil properties from a grid of point samples
- use of soil/landscape models with input from either remote sensing or a digital elevation map (DEM)

Multispectral images

Despite the relations among soil reflectance and soil properties, remotely sensed images are not currently being used to map soil characteristics on a routine basis. This is because the reflectance characteristics of the desired soil properties (e.g., organic matter, texture, iron content) are often confused by variability in soil moisture content, surface roughness, climate factors, solar zenith angle, and view angle.

3 Mapping Seasonally Variable Conditions

Soil Moisture Content

Information on within-field soil moisture variation throughout the season has been shown to be relevant to decisions made about:

- tillage activities (Lindstrom et al., 1995)
- nitrogen applications (Hug-gins and Alderfer, 1995; Sadler et al., 1995)

Soil Moisture Content has been usually monitory through SAR technology.

Crop Phenology

Knowledge of the stage of the crop development is useful for time-specific crop management such as:

- minimizing or maximizing crop stress during crucial periods (e.g., grain filling in wheat, anthesis of corn, or sugar development in cantaloupe).

For example, the vegetative, reproductive and senescing phases of wheat crops have been discriminated based on:

- seasonal shifts in the red edge (Railyan and Korobov, 1993)
- bidirectional reflectance measurements (Zipoli and Grifoni, 1994)
- measurements of reflected polarized light (Ghosh et al., 1993)
- temporal monitoring of NDVI (Boissard et al., 1993).

Crop Growth

The most common approach in remote sensing for measuring or monitoring crop growth is the empirical correlation of VI with such crop variables as LAI, percent veg-etation cover, vegetation phytomass and fraction of absorbed photosynthetically active radiance. The basic theory of this approach is well understood (Jackson and Huete, 1991); and recent improvements to this approach include developing VIs are that insensitive to soil/atmosphere/sensor noise (e.g., Huete, 1988; Malthus et al., 1993) and developing empirical relations that are robust for application to a variety of crops, locations, and conditions (Richardson et al., 1992; 1993; Wie-gand et al., 1992).

Other approach is based on crop growth models. An example of the former was presented by Clevers et al. (1994) using optical reflectance measurements to calibrate the SUCROS crop growth model and improve estimates of crop yield.

Other approach is based on canopy radiative transfer models (RTM). An example of the latter was presented by Kimes et al. (1991) in the development of a knowledge-based system (VEG) to infer reflectances of a vegetation target, or inversely, to derive vegetation characteristics from multiband or multiview reflectance measurements.

Crop Stress through Evapotranspiration Rate

Crop stress be a consequence of:

- nutrient deficiency
- crop disease
- water deficiency
- some insect infestations
- other problems

Due to the fact that crop stress is often manifested by a decrease in the transpiration rate of the crop, some work has been conducted to use remote sensing for monitoring crop evapotranspiration rates.

One of the more promising approaches for operational application is the use of remotely sensed *crop coefficients* (the ratio of actual crop evapotranspiration and that of a reference crop) for estimation of actual, site-specific crop evapotranspiration rate from readily available meteorological information. This approach requires only a measure of spectral vege-tation index like NDVI. (e.g., Bausch, 1993)

Another approach that has obtained commercial success is the *crop water stress index* (CWSI), which provides a measure of crop stress from 0 to 1 based on the difference between surface and air temperature with reference to the vapor pressure deficit and a crop-specific baseline (Jackson et al., 1981, Moran and Jackson (1991) and Norman et al. (1995)].

Crop Nutrient Deficiency

Plant nitrogen content and canopy nitrogen deficits have been related to reflectance measurements in the green (0.545 pm), red (0.66 pm), and NIR (0.80 pm) spectrum (Fernandez et al., 1994; Buschmann and Nagel, 1993). However, most such relations are sensitive to variations in soil reflectance, and the best bandwidths are narrow and unavailable with satellite-based wide-band sensors.

Crop Disease

Though wide visible and near-infrared bands may be helpful for discriminating healthy and diseased crops (due to changes in foliage density, leaf area, leaf angles, or canopy structure), the best results for identifying diseases were obtained with hyperspectral information in the visible and near-infrared spectrum. Discrimination of diseases may be possible with knowledge of the physiological effect of the disease on leaf and canopy elements. For example:

- necrotic diseases can cause a darkening of leaves in the visible spectrum and a cell collapse that would decrease near-infrared reflectance.
- chlorosis inducing diseases (mildews and some virus) cause marked changes in the visible reflectance (similar to N deficiency).
- other diseases may be detected by their ef-fects on canopy geometry (wilting or decreases in LAI).

Weed Infestation

For precision management of pre-plant applications, the information requirement is simply determination of presence or absence of plants, and the remote sensors (e.g., Richardson et al., 1985) should be comparably simple, such as:

- the tractor-based sensors
- interpretation of digital images based on VI
- supervised classification

For precision management of postemergence herbicide applications, it is required discrimination between weeds and crops. This is generally accomplished based on:

- the differences in the visible/NIR spectral signatures of crops and specific weeds (Brown et al., 1994)
- by acquiring images at specific times during the season when weed coloring is particularly distinctive (i.e., during flowering).

Insect Infestation

Indirectly, insect damage to plants has been detected through remote sensing of:

- insect habitat (Hugh-Jones et al., 1992)
- growth and yield of plants (Vogelmann and Rock, 1989)
- changes in plant chemistry

4 Determining Causes of Yield Variability

Remote sensing has a variety of roles in determining the cause of spatial and temporal crop and soil variability.

- use of hyperspectral imagers for direct crop diagnosis. In this review we have cited examples where hyperspectral data in the visible and NIR wavelengths have been used successfully for discrimination of crop stress caused by nutrient deficiency, crop disease, water stress, and more.

- use of remote sensing information to improve the capacity and accuracy of DSS and agronomic models by providing accurate input information or as a means of model calibration or validation. The link between remote sensing and simulation modeling has been illustrated through examples of the use of remote sensing for parameterization of models (Wiegand et al., 1986b), within-season model calibration (Maas, 1993), and model validation (Fischer, 1994).