comparison is easier. For example, if benefits are expressed in terms of costs saved, and if cost data are available, then benefits and costs can be compared (Bouma and coauthors make this comparison, for instance). If benefits and costs are combined, a general rule of thumb in benefit and cost assessment is that the *difference* between benefits and costs is preferred to the ratio between benefits and costs. Using the difference avoids the problem of whether a benefit is a negative cost, which can lead to ambiguous results when using the ratio rather than the numerical difference. (An example: In estimating the benefits of remote sensing in monitoring air pollution, is a reduction in pollution a benefit or an avoided cost? Expressing the reduction as a benefit or a cost will not affect the difference but will affect the result if benefits and costs are expressed as a ratio.)

Conclusion

Assessing the benefits and costs of remote sensing is one of the challenges of ascertaining the appropriate amount of investment a society should undertake in remote sensing systems. When is the cost of these systems justified by the benefits they confer? For a variety of reasons, quantifying costs and benefits is difficult. Expressing benefits in financial terms is particularly difficult, as remote sensing data may confer benefits in the form of new knowledge or about natural resources (air, water, climate, land, oceans) and the environment (air and water quality, land use). Society values these benefits, but ascribing monetary value to them is quite difficult.

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Cross-references

Commercial Remote Sensing
Data Policies
Emerging Applications
Environmental Treaties
Mission Operations, Science Applications/Requirements

CROP STRESS

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Synonyms

Insect infestation; Nitrogen deficiency; Water deficiency; Weed infestation

Definitions

Crop stress. Crop response to environmental factors that results in suboptimal crop production.

Introduction

Crop stress is the plant response to environmental factors that ultimately results in suboptimal crop production. The environmental factors of primary interest to US corn, cotton, soybean, and wheat producers are water, nutrients, weeds, and insects. Not coincidentally, these are also the factors that are most easily managed through irrigation and applications of fertilizer, herbicides, and pesticides. Crops are generally managed to minimize crop stress within the constraints of producing a profitable yield and minimizing environmental impact. The day-to-day management decisions to achieve this delicate balance are based in part on information about the extent, duration, and cause of crop stress. The role of remote sensing in crop management is to provide such information about crop stress using sensors that acquire data in the visible (VIS), near-infrared (NIR), short-wave infrared (SWIR), thermal infrared (TIR), and synthetic aperture radar (SAR) wavelengths. A first step is to understand the physical plant manifestations associated with crop stress that are most easily detected with optical and microwave remote sensing.

Plant manifestations of crop stress

Water stress affects the plant leaf canopy by two primary mechanisms (Rosenthal et al., 1987). The first involves the closure of leaf stomata, which results in a reduction in photosynthesis and transpiration. The associated increase in leaf temperature can be detected using remote sensing in the thermal infrared wavelengths (Jackson et al., 1981). The second mechanism involves a decrease in leaf expansion and an increase in leaf senescence. The reduction in plant leaf canopy development in comparison to well-watered plants can be detected through estimates of LAI or ground cover made using remote sensing in the visible wavelengths (Maas and Rajan, 2008). The mechanism affecting leaf stomata is initiated when available soil water in the root zone falls below 30 %. In contrast, the mechanism affecting leaf expansion and senescence is initiated when available soil water in the root zone falls below 50 %. Thus, leaf expansion and senescence typically are affected by water stress before photosynthesis and transpiration. There are a number of secondary effects of water stress that are associated with the adaptation of plants to the decrease in water availability.

The crop physiological adaptations to transient water deficit range from changes in canopy architecture to adjustments in leaf osmotic potential (Turner, 1977). Many of these adaptations have a pronounced effect on spectral reflectance and SAR backscatter and the optical properties of plants that allow stress detection with remote sensing. Crops have the capacity for developmental plasticity to complete the life cycle before serious water deficits develop. For example, studies have shown that wheat can hasten maturity in response to mild water deficits at the critical time between flowering and maturity. To endure prolonged water deficit while maintaining high water potential, some crops reduce water loss through increased epidermal waxes of leaves and a reduction in general plant productivity. Other adaptations are to reduce the radiation absorbed by the plant through leaf movement (e.g., leaf cupping, paraheliotropism, or wilting) or to reduce leaf area through decreased leaf expansion, reduced tillering and branching, and leaf shedding. It is generally reported that leaves under water stress show a decrease in reflectance in the NIR spectrum and a reduced red absorption in the chlorophyll active band (0.68 μm); however, Guyot et al. (1984) found that it was necessary to have an extremely severe water stress to affect the leaf reflective properties. In the TIR, there is a direct link between the process of plant water evaporation and the plant thermal response (i.e., water evaporates and cools the leaves) explained by Jackson et al. (1981).

Like crop water stress, crop nutrient stress has a direct effect on crop growth and development. Nitrogen is frequently the major limiting nutrient in agricultural soils. Leaves deficient in nitrogen absorb less and scatter more visible light (Schepers et al., 1996). Due to the link between leaf chlorophyll and nitrogen concentrations (Daughtry et al., 2000), leaves marginally deficient in nitrogen may appear a lighter, less saturated shade of green, and more severely nitrogen-stressed leaves may appear yellowish green and chlorotic. Thomas and Oerther (1972) found that with nitrogen deficiency, the visible reflectance increased (due to decreasing chlorophyll content) and the NIR and SWIR reflectances decreased (due to decreasing number of cell layers). Nutrient deficiencies in crop canopies have the potential to affect canopy architecture and the optical properties of not only the leaf but also the stem and flower/grain head. Manifestations of typical nutrient stresses generally appear initially as changes in the optical properties of leaves and only later as change in the canopy architecture and decreased canopy biomass. The position of the red edge (an abrupt, step increase in the leaf reflectance in the NIR around 0.72 μm just outside the visible region) offers a robust metric for monitoring leaf and canopy nutrient status (Peñuelas and Filella, 1998). Recently, the concentration of epidermal polyphenolics, secondary metabolites in the leaf that may be measured using a commercially available clip-on UV absorption meter, has shown promise as a surrogate measure of leaf nitrogen status (see, for example, Tremblay et al., 2007; Demotes-Mainard et al., 2008; Meyer et al., 2006).

Crop stress due to weed interference has been attributed to many factors, including allelopathy and competition for sunlight, soil water, and nutrients (Sikkema and Dekker, 1987). The plant manifestation of weed-induced crop stress is generally reduced crop yields. Because weed distribution is influenced by drainage, topography, soil type, and microclimate, crop stress in weed-infested fields is highly variable. Variations in reflectance patterns and canopy temperatures over time and space may reveal crop stress associated with soil and topographic conditions (Wiles et al., 1992). In the early season, herbicide application is based simply on the presence or absence of plants, and remote sensing systems generally use the reflectance differences between relatively wide spectral bands in the visible and NIR spectra to make the distinction between plants and soil or rock (Medlin et al., 2000). Post-emergent herbicide applications require discrimination between weeds and crops, which is generally accomplished by using the difference between spectral signatures of crops and specific weeds or by acquiring images when weed coloring is particularly distinctive (Brown et al., 1994) or weed patches are comparatively large, dense, and/or tall (Pérez et al., 2000).

Remote sensing is not used to directly observe insects, but rather, to observe the damage to crop foliage and to detect plant canopy conditions that might be conducive to insect infestation. Early infestations of some insects are associated with leaf senescence or mortality, resulting in reduction in canopy density. Some crop pests not only cause physical damage to the leaf canopy but also cause a change in the spectral reflectance characteristics of the affected foliage. Aphids (*Aphididae*) deposit honeydew on cotton leaves which supports the growth of sooty mold (*Aspergillus* spp.), thus profoundly affected the reflectance characteristics of the leaves, particularly in the NIR (Maas, 1998). Other pests, such as spider mites (*Tetranychus* spp.), can cause changes in leaf reflectance that can be detected using remote sensing in the visible and NIR wavelengths (Fitzgerald et al., 2001, 2004). These spectral signatures are distinct enough to differentiate them from water stress effects (Fitzgerald et al., 2000). Insects are sometimes attracted to areas within fields that contain the most vigorous plant growth. Areas of lush cotton growth in Louisiana were identified with spectral vegetation indices to direct scouting for the tarnished plant bug (*Lygus lineolaris*) and facilitate spatially variable insecticide applications (Willers et al., 2000).

Remote sensing of crop stress

Readers are referred to recent reviews by Moran et al. (2004) and Hatfield et al. (2004) for an extensive summary of remote sensing applications and products for detecting crop stress associated with water and nutrient deficiencies and weed and insect infestations. The greatest progress has been made in crop water stress detection. The use of remote sensing in irrigation scheduling has been reviewed by Maas (2003). Some spectral crop water stress indices have been commercialized for irrigation scheduling (Jackson et al., 1981; Burke et al., 1988). Opportunities for deriving crop nutrient status and pest infestation from remote sensing have recently increased with the development of hyperspectral and narrowband multispectral imaging sensors (Gitelson et al., 2006; LaCapra et al., 1996). The production of fine-resolution digital elevation models (DEM) with high vertical accuracies from radar systems provides useful supplemental information for the management of large agricultural areas. Recent development and launches of multispectral sensors with fine resolution has stimulated efforts to observe the early stages of pest infestations and areas with potential for pest infestations in time for control measures (Fitzgerald et al., 2004).

Conclusions

The technologies of the future will probably include sensors to measure natural and genetically induced fluorescence related to crop vigor (e.g., Liu et al., 1997), more focus on multispectral data fusion including SWIR, TIR, and microwave measurements (e.g., Jackson et al., 2004), and increased assimilation of remotely sensed data in crop yield models and decision support systems (e.g., Maas, 2005; Baez et al., 2005; Maas, 2005; Ko et al., 2005, 2006). The latter has the potential to address one the greatest challenges to use of remote sensing as a source of information about crop stress – determining the cause of crop stress. It has been particularly difficult to discriminate crop stress due to water and nitrogen, which often produce similar plant manifestations but require different and costly management. Decision support systems based on crop growth theory can assimilate producer knowledge, management history, and remote sensing information to best determine the extent, magnitude, and cause of crop stress. This could lead to the turnkey solution called for by Hatfield et al. (2008) for application of remote sensing for agronomic decisions suited to both specialists and nonspecialists.

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Cross-references

Agriculture and Remote Sensing
Data Assimilation
Irrigation Management
Precision Agriculture
Soil Moisture
Soil Properties
Vegetation Indices
Vegetation Phenology

CRYOSPHERE AND POLAR REGION OBSERVING SYSTEM

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Definition

Cryosphere. It collectively describes elements of the Earth system containing water in its frozen state and includes sea ice, lake and river ice, snow cover, solid precipitation, glaciers, ice caps, ice sheets, permafrost, and seasonally frozen ground. Although a significant portion of the world's snow and ice is found in the polar regions, cryosphere exists at all latitudes and in about 100 countries.

Polar regions. Earth's polar regions are the areas of the globe surrounding the north and south poles typically encompassed by a line of latitude corresponding to 66° 34′ north or south (i.e., between each pole and its corresponding polar circle), which is the approximate limit of the midnight sun and the polar night. Alternatively, it can be defined as the region where the average temperature for the warmest month (July) is below 10 °C (50 °F).

Introduction

Knowledge of the state of the cryosphere is important for weather and climate prediction, assessment and prediction of sea level rise, availability of freshwater resources, navigation, shipping, fishing, mineral resource exploration and exploitation, and in many other practical applications (IGOS, 2007). Changes to the cryosphere have far-reaching climate and socioeconomic consequences. The need for reliable global monitoring is essential to address the issues of climate and cryosphere within the Earth system. Despite its importance, the cryosphere remains one of