Applications of Remote Sensing in Agriculture

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REMOTE SENSING IN AGRICULTURE: PROGRESS AND PROSPECTS

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Impressions

I believe that most participants at this Easter School will return to home base with three abiding impressions of what we have heard and seen. First, we have been left in no doubt that techniques of remote sensing are continuing to develop very rapidly, particularly in the interpretation of microwave signals and in the storage and processing of data. Second, platform speakers, along with all the enthusiasts who displayed posters, have convinced us that there are many ways in which remote sensing could, in principle, be deployed to increase the world's food supplies. Third, speakers from the floor have repeatedly pointed out that the contribution which remote sensing has so far made to agriculture lags far behind the perceived potential. In attempting to sum up conclusions from this meeting, I shall be specially concerned with the constraints which prevent that potential from being realised.

Evolution of remote sensing

Most applications of remote sensing are still in the process of evolving through stages of development familiar in the experimental sciences. After the first flash of inspiration come measurements and hypotheses, usually in that sequence but sometimes in the reverse. Hypotheses suggest how measurements should be interpreted in terms of underlying mechanisms and the number of measurements needed to support a given hypothesis often displays a broad optimum. Below the optimum, experimental support for the hypothesis is unconvincing. Above the optimum, attempts to demonstrate the validity of a hypothesis can be obscured by a fog of facts. Remote sensing often demonstrates this problem. Enormous amounts of data are generated by instrumentation on orbiting satellites but usually only a small fraction is subsequently used. Data banks, however comprehensive, cannot generate hypotheses spontaneously. This process is always limited by the human "eye-brain" system that Allan talked about, and in many remote sensing laboratories the ratio of minds to megabytes seems very small!

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The next step is to use hypotheses, singly or in groups, to generate what used to be called a "theory" but which is now usually referred to as a "model". A model is a quantitative description of a system derived from a limited set of data but capable of predicting how it will behave in response to changes either in the external environment or within the system itself. We have considered several types of agricultural models, but have concentrated on dry matter production and light interception by canopies (papers by Kanemasu and Prince), and on the relation between transpiration rate and surface temperature (papers by Campbell and Guyot). I shall return to both these areas. Models

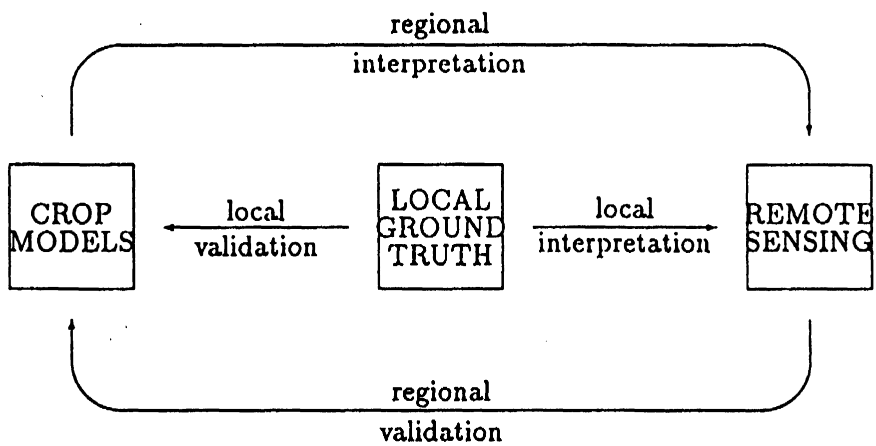

FIGURE 23.1. Interaction of remote sensing and crop models.

and remote sensing can usefully reinforce each other, as *Figure 23.1* suggests. Neither can progress far without "ground truth" on the scale of a single field (for models) or of a few pixels (for remote sensing). Models which have been validated by appeal to ground truth (which is usually limited in scope and sometimes not entirely truthful), can be used on a regional scale to interpret imagery from aircraft or satellites in terms of the state of soil and/or vegetation. Similarly, the application of models on a regional scale can be validated by using remote sensing, in the form of satellite images for example, to provide independent estimates of crop yields.

Eventually, a good model should be extracted from the perfectionist clutches of its creators and used to improve the management of an agricultural system. The sophisticated scheme for managing water resources in part of the Netherlands, described by Nieuwenhuis, was one of the few cases we heard of where this last step had been successfully reached.

I have suggested that a disproportionate amount of effort seems to have been expended on the data-collecting end of remote sensing, but it is only fair to recognize that this is typical of a discipline in the Natural History phase of its development (so it was unkind of Rutherford to describe biologists as "stamp collectors"!). The historical background to this state of affairs is that most satellite technology was developed for military surveillance. Applications to earth resources in general and to agriculture in particular are therefore a bonus; but Evans and other speakers reminded us that simpler techniques, like aerial photography, may often provide quicker and more precise answers to agricultural problems.

Models of agricultural systems have lagged behind the availability of measurements from aircraft and satellites because most have relied for their validation on sets of observations made at a very limited number of sites. Management has lagged further behind still because farmers and their advisers remain unconvinced that satellite technology can beat inherited skills. This point of view is justified at present: there is no evidence that the invention of the telescope in 1608 encouraged farmers to direct field operations from their bedroom windows!

Evaporation

To derive his formula for estimating evaporation, Penman (1948) deliberately eliminated surface temperature as a variable because, 40 years ago, it was hard to observe in the field and even harder to record. For the measurements needed to establish a wind function, he was forced to use cumbersome mercury-in-steel thermometers to record the surface temperature of water in evaporation pans.

In the 1960s, the development of compact and fairly stable radiation thermometers that could be operated in the field made it possible to measure the Radiative Temperature (T_r) of soils and crops to about 1K and encouraged a reassessment of Penman's algebra to see what additional information could be obtained about responses of crops to their water supply. The USDA group in Phoenix, Arizona, became the main exponents of techniques for using measurements of T_r to assess rates of evaporation from crops, shortage of water in terms of "stress degree days" and implications for yield (Idso, Jackson and Reginato, 1977). However, other groups working at cloudier sites with random fluctuations of solar radiation found it more difficult to interpret T_r in terms of crop water supply.

More problems arise when T_r is measured from a satellite, because of calibration drift and because of the need to correct for atmospheric absorption and emission. These topics have barely been touched on at this meeting but cannot be ignored in any realistic assessment of the potential for remote sensing in agriculture. Errors can be large when latent heat loss is estimated from the difference between net radiation and sensible heat loss and when the sensible heat calculation involves the difference between T_r and the temperature at screen height measured with a completely different system. Error can be minimized by using a reference surface (Nieuwenhuis) but even then it is desirable to have additional information about aerodynamic surface characteristics and about weather at screen height (Gash, 1986).

I therefore believe that agronomists, like hydrologists and ecologists, are likely to have to wait for some years before remote sensing can provide them with estimates of evaporation better than what is now available from formulae that incorporate an informed guess about the magnitude of a surface resistance. Microwave radiometry, as described at this meeting by Luzi, Paris and Holmes, has a number of potential advantages, including the ability to penetrate clouds, to measure soil water (but only close to the surface), and to monitor changes of plant water content. Another type of remote sensing (referred to by Kanemasu) is the use of eddy correlation equipment on low-flying aircraft to measure fluxes of both water vapour and CO_2, so that water-use efficiencies can also be found, as described by Schuepp, Austin, Desjardins, MacPherson and Boisvert (1987). This is a powerful way of exploring transfer processes in the atmospheric boundary layer, but costs are likely to remain prohibitive for most agricultural applications.

Dry matter production

Several papers and posters have demonstrated how remote sensing can be used to estimate rates of dry matter accumulation by crop stands, given daily mean values of incoming solar radiation and the fraction of that radiation intercepted by foliage as obtained from its spectral characteristics. It is customary to work with wavebands just below and just above a wavelength of 700 nm to give maximum discrimination between foliage and underlying soil, but this is a small fraction of the spectral information available from most satellites. I agree with Steven that more effort should now be spent on looking at derivative spectra and at other wavebands to obtain indices that can be correlated with stress. It may also be possible to obtain more precise information about seasonal and secular changes of ground cover by combining measurements of the Normalised Difference Vegetation Index, (NDVI) with microwave polarization differences (Becker and Choudhury, 1988).

To estimate rates of dry matter production during the growing season and final yield, it is necessary to know the appropriate value of e – the mass of dry matter accumulated per unit of radiation intercepted (This quantity is often referred to as a "radiation use efficiency" but it is not a true efficiency until it is multiplied by the energy equivalent of biomass). Many systematic measurements of e for field crops have been reported recently (e.g. Kiniry, Jones, O'Toole, Blanchot, Cabelguenno and Spaniel, 1989) and have prompted me to examine the question of whether e and the corresponding water use efficiency can both be conservative at the same time (Monteith, 1989). The answer appears to be "Yes, to a good approximation when water supply is unrestricted; no, when there is a shortage of water". Nutrient shortage appears to operate in the same way but on a restricted scale (Green, 1987).

The first response of most plants to drought (or nutrient deficiency) is to slow the expansion of leaves and to allocate a larger fraction of current assimilate to extending roots. This helps to keep water supply and demand in balance and to stabilize the value of e.

In contrast, if stress builds up rapidly when a plant has a substantial amount of foliage to support, closing stomata is the only way in which the demand for water can be reduced to the level of supply. Because stomatal resistance has to be more or less proportional to demand, it is often found to be a strong function of saturation vapour pressure deficit in these circumstances. Stomatal closure reduces the photosynthesis rate per unit of intercepted radiation and therefore the value of e. At present we have no reliable way of estimating the non-potential value of e because so little is known about how the size and activity of the root system determines the maximum rate of water supply. However, it may be possible to obtain useful guesses of non-potential e by correlating measurements of e at the ground with the rate of change of vegetative cover determined spectrally. In this case, differences of population would need to be taken into account.

Prince gave an impressive demonstration of how values of e characteristic of vegetation in a semi-arid part of West Africa (and clearly sub-potential) were obtained from careful sampling on the ground and from satellite records. Without more ground studies of this type, enormous amounts of valuable information will be archived and eventually destroyed unused - a tragic waste of resources.

Time and space

As Allan pointed out at the beginning of this meeting, the agricultural potential of remote sensing is circumscribed by limitations of space and time. On the scale of hours to days, farmers in many parts of the world already obtain weather forecasts developed with the help of satellite images of cloud systems and interpreted in terms of the timing of rainfall, extremes of temperature, risk of high winds, etc. In relatively unpopulated regions, where observing stations are sparse, remote sensing should play a much more central role in forecasting weather. The technique for estimating rainfall from cloud-top temperature as described by Milford is a most encouraging example of this process and it is reassuring to know that FAO is now involved through its ARTEMIS project.

Still within a relatively short time-scale, but on a larger scale spatially, satellite images, released internationally and in "real" time could provide governments and extension services with the information they need to monitor and control fungal epidemics and pest invasions, to assess surface water resource for irrigation schemes, to monitor the extent of floods, etc.

On a medium time-scale (weeks to months), the main potential for remote sensing appears to be in the assessment of crop growth rates as a basis for predicting yield and as an index of the need for irrigation, application of fertilisers, control of disease, frost protection, etc. As an example of a successful regional survey, the contribution from Brooms Barn Experimental Station by Jaggard and ClarK described how annual sugar production was estimated from the spectral properties of radiation reflected from representative fields of beet and regularly monitored from a light aircraft. Observations from a satellite are now being used at the WMO regional centre in Niger (AGRHYMET) to assess rainfall distribution and the seasonal progress of crop production in the western Sahel. Both China (Zheng Dawei) and India (Sahai and Navalgund, 1988) are using satellites in this way, despite problems created by small farm sizes, the prevalence of mixed cropping and extensive cloud cover during rainy seasons.

On a much longer time-scale (years) the main potential of remote sensing appears to be the development of detailed inventories for soils and crops, a process likely to become much faster and more efficient with the development of the Geographical Information Systems referred to by several speakers; the accumulation of crop histories over several consecutive years as a basis for improving assessments of stress and yield; and the monitoring of land degradation as a consequence of pollution, erosion, poorly designed irrigation schemes, etc.

Postscript

In a rapidly developing field of research and technology, it is dangerous to pontificate about what may or may not be possible in the foreseeable future. I have felt bound to speculate a little but find it salutary to recall how ignorant I was of the potential for remote sensing when the first Sputnik started bleeping its way round the world in October, 1957. The Annual Report of Rothamsted Experimental Station for 1957, which appeared a few months later, contained these words: "Measurements of reflection coefficient may give useful estimates of leaf growth without destructive sampling". When I wrote that, it never occurred to me that my crude, home-made solarimeters would be replaced within my lifetime by satellite-borne radiometers, scanning the continents to estimate net primary production from a Normalised Difference Vegetation Index.

The continuing development of satellite and space station technology makes it impossible to predict what remote sensing may be able to do for agriculture in another 30 years or even in 10. As we consider the surpluses of food which now embarrass many western countries, it is clear that two items should appear high on the agenda for agricultural remote sensing: (a) increasing food production and distribution in countries with chronic malnutrition and widespread poverty; and (b) in all parts of the world, endeavouring to identify and then to minimize damage to the environment caused by agricultural practices. As several participants have pointed out, the achievement of these goals calls for the political will to stimulate both national and international action and to remove scientists from "the bottom of the pecking order" when priorities are assigned for access to data.

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