Agrometeorological Models and Remote Sensing for Crop Monitoring and Forecasting in Asia and the Pacific[α]

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1. Introduction

The first section of this note provides some insight into the rather intricate subject of determining the actual role of weather in crop yield variability in quantitative terms.

The following sections give an overview on the methods currently used to assess the impact of weather conditions on crop yields quantitatively: they include mainly crop-weather modelling combined with new sources of information such as remote sensing.

As in many other areas, crop modelling technology, tools and methods have undergone rapid developments in the recent years, an evolution mainly driven by technology, from computers to communications. With the due caveats listed below, the following can be seen as major tools available in crop-weather impact assessments: (1) Process-oriented models, (2) GIS techniques, geostatistics and random weather generators (RWG), and (3) Satellite inputs.

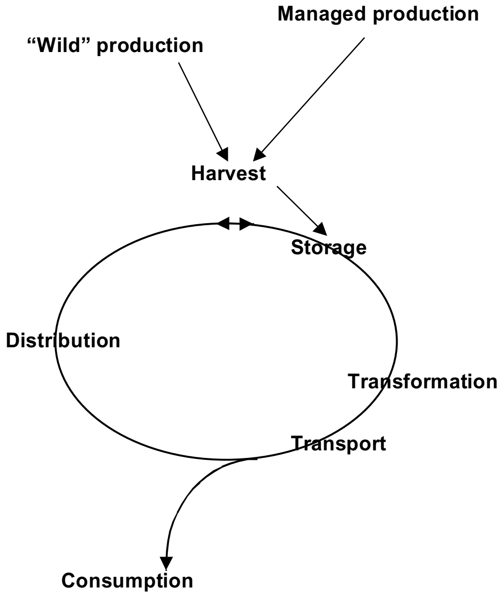
Process-oriented models were mostly designed in a research context for use at the scale of a field. They require considerable simplification to be usable under operational conditions. GIS techniques, geostatistics and RWGs are now well established tools. They have become part of all agrometeorological modelling of weather impacts on crops. Satellite inputs are somehow lagging behind both their potential and their reputation…. This can be explained by several factors, including cost, lack of proper information of users, and the availability of the products.

2. What are the factors behind the inter-annual variability of yields?

Time series analysis of agricultural statistics shows that the inter-annual variability of crop yields roughly stems from three sources: (i) trend, (ii) direct weather factors and (iii) indirect weather effects, pests, diseases, weed competition, etc. The issue of weather impact on food availability is further complicated by the fact that weather plays a part at several levels of the food production chain, as illustrated below in figure 1.

The spectrum of the sources of weather-induced variability is thus rather wide and includes a number of direct and indirect factors: it includes water availability and sunshine, pollination, animal and crop pests and diseases, trafficability, transport of pathogens by wind, irrigation, food storage, phenology, etc.

Figure 1: Agrometeorology deals with all the weather-sensitive components of the chain leading from production to consumption of all agricultural products, specifically including animals and plants (after Gommes, 1998a).



The relative importance of the listed sources of the variability of food production depends largely on the general socio-economic setting. In many developing countries, the technology component is not very marked, and some countries among the poorest show no yield trend at all. This is a situation where the impact of weather can have dramatic conditions and threaten the food security of millions of people. When the same farmers will be gradually forced by circumstances to adapt to more commercial farming, they will go through a transition phase where their vulnerability to weather vagaries will increase.

Where the agricultural sector is more advanced (mechanisation, irrigation, improved varieties and advanced on-farm decision-making, etc.) the trend accounts for a large portion of the variability of yield (80% and more). Figure 2 illustrates this behaviour in the instance of Bangladesh. The remaining 20% (or less) is shared about equally between weather, and pests and diseases (Oerke et al., 1994), of which many are also weather dependent. If the trend is removed from the time series, we can therefore assume that the largest fraction of the residual variability is due to weather.

The relative importance of weather variability also largely depends on the scale adopted for the assessment. At the low levels of aggregation, the variability increases, as shown in figures 3 and 4, while at the national level, where several cropping seasons and typologies are aggregated, the effect of weather is far less marked.

Extreme agrometeorological events are factors, which often are at the same time rare (low statistical frequency) and characterised by high intensities. They include for instance large pest outbreaks, fire, torrential rains, tropical cyclones, etc. They can provoke massive destruction of infrastructure, crops, livestock, fishing gear, etc. and the loss of human life (Gommes, 1999a, 1999c).

Figure 2: Trends of total rice yields in Bangladesh since 1972

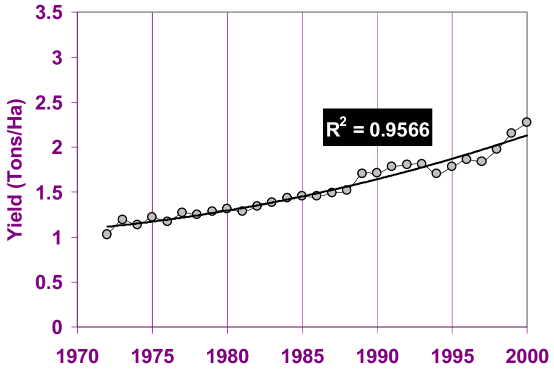


Figure 3: Trends in rice crop yields in Bangladesh according to cultivation typology: early monsoon crop (Aus), late monsoon (Aman) and irrigated winter crop (Boro).

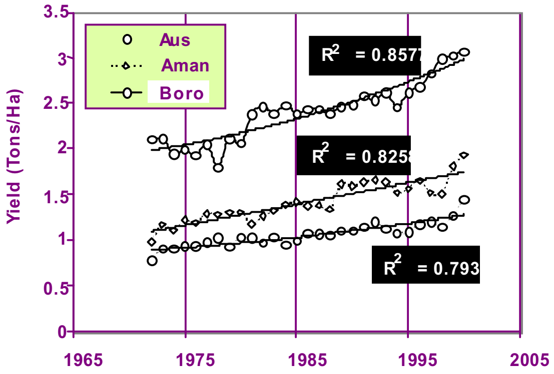
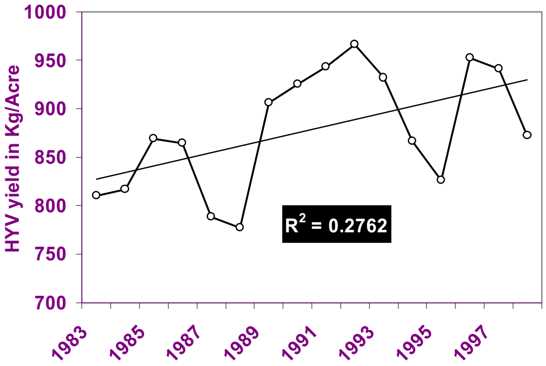


Figure 4: T-Aman rice yields in Rajshahi upazila (district) between 1985 and 1998



A most important observation regards the impact of extreme factors. Normally, in spite of the massive destruction they can bring about at the local level and at a very precise time, their impact remains far less that the losses brought about by the chronic deficiencies of weather such as droughts, local pest attacks, biodegradation of agricultural materials, hail, etc.

Extreme events are not dealt with in this paper for methodological reasons[1] and because far more losses are associated with the chronic and inconspicuous effects of climate variability.

3. Crop yield simulation models and statistical "models"

A model is a programme (and the science behind it) that simulates (predicts) the behaviour (output) of a plant (e.g. yield) based on environmental conditions (inputs, incl. management) and variables describing the plant's ecophysiology (parameters). There is in fact a large variety of models (as well as associated problems) which cannot be described here (refer to Gommes 1999b).

Figure 5: Schematic representation of a crop simulation model showing the interaction between environmental factors, crop growth and development, and management.

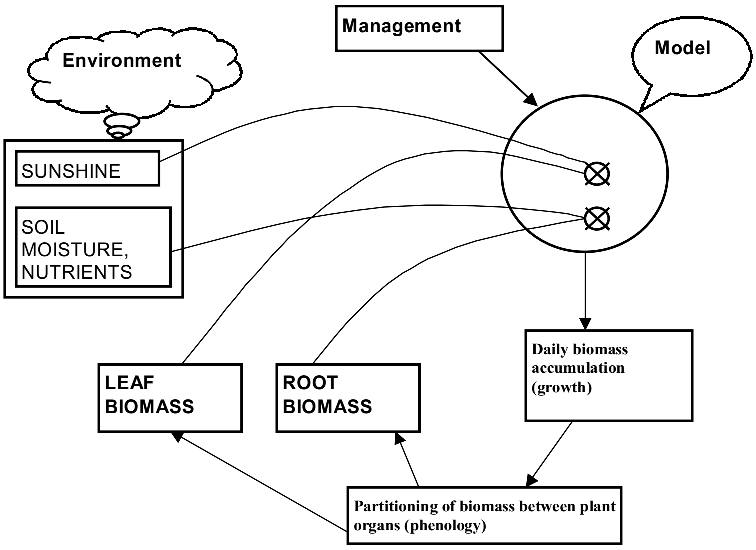


Figure 5 schematically illustrates the operation of a typical model: a model "estimates" the effects of management and environment on plant growth and development. In practice, a model is an accounting system that keeps track of the amount of biomass stored in the different organs. On a daily basis, such variables as leaf area, sunshine, water and nutrient availability are compared to each other and the model determines the amount of plant material (biomass) that can be accumulated (daily growth, to be added to the old biomass). The daily growth is subsequently distributed among plant organs. The next day, the new biomass is exposed to the environmental conditions, etc.

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[1] The effects of extreme factors on agriculture are difficult to model because of their sporadic nature. Preventive measures and warning systems require investments that exceed by orders of magnitude those used for the "normal" meteorological factors. In addition, extreme factors are normally dealt with by the National Meteorological Services in the Ministry of Transport, Public Works etc., and only rarely in Ministries of Agriculture

Models must be calibrated, i.e. verified and fine tuned by comparison against a number of actually measured parameters, for instance soil moisture, soil nutrient content, actual biomass accumulation and yield, etc.

Statistical “models” are multiple regression equations used to estimate crop yield as a function of one or more agrometeorological variables, for instance

$$\mathrm{Yield} = 5 + 0.03\,\mathrm{Rain}_{\mathrm{March}} - 0.10\,\mathrm{T}_{C,June}$$

with yield in tons Ha^{-1} , March rainfall in mm and June temperature in °C. Beyond their simplicity, their main advantage is the fact that calculations can be done manually, and in the fact that data requirements are limited. The main disadvantage is their poor performance outside the range of values for which they have been calibrated. They often also lead to unrealistic forecasts when care is not taken to give greater priority to the agronomic significance than to statistical significance. The equation above, for instance, suggests that low March rainfall (a negative factor) could be corrected by below zero temperatures in June (frost), which obviously does not make sense.

Another disadvantage is the need to derive a series of equations to be used in sequence as the cropping season develops. For an overview of regression methods, including their validation, refer to Palm and Dagnelie (1993) and to Palm (1997a).

Many of the disadvantages of the regression methods can be avoided when value-added variables are used instead of the raw agrometeorological variables, as is done normally in crop forecasting systems set up with FAO assistance. Such a value-added variable would be, for instance, actual crop evapotranspiration, a variable known to be linked directly with the amount of solar radiation absorbed by the plant under satisfactory water supply conditions or light water stress. Value-added variables are often obtained through the use of simple simulation models.

4. GIS techniques, geostatistics and random weather generators (RWG)

Models operate based on data from a specific location (a point), but crop forecasts need to be issued for larger administrative regions, such as districts, provinces, etc. The set of techniques wich are used to convert point data to larger areas belong to geostatistics (statistics of spatial data) and to Geographic Information Systems (GIS). Finally, weather conditions are normally not known at the exact location where a model is run. Geostatistical tools are now widely used to estimate weather condition at the location where a model is being run, although there is no meteorological station.

Since forecasts are issued while the crop is still growing in the field, there is also the need to estimate what the likely weather will be between the time of the forecast and harvest. For instance, assume that we are forecasting the yield of a crop planted in November and due to be harvested in May. Assume we are currently at the end of February, so that the actual weather conditions from November to February are known. We have to make some assumption for the “future” weather between March and May: we need i.e. a set of 30 or 50 years of weather data that may realistically occur. This will result in 30 or 50 yield estimates, the average of which can be taken as the current forecast.

There are several techniques, but a very common one is to resort to Random Weather Generator, a computer programme that generates synthetic weather series for a given location, based on the historical data for the station being investigated. In the words of Göbel (1995), synthetic series are not forecasts of what will happen in the future but rather samples of sequences of events which might happen.

They are extremely useful for many applications, from risk evaluation to crop forecasting.

RWG simulate the correlation and stochastic processes (Markov chains) that are present in the historical data. The processes are controlled by coefficients that are site specific. The coefficients driving a generator may be mapped (spatially interpolated) like any other variable, thus providing the possibility to generate synthetic weather covering large areas. Note that in most cases there is no spatial coherence in the thus generated fields.

Of the associated models and tools, Geographic Information Systems have become ubiquitous. GIS techniques are used to prepare the spatial input data for the regional applications; they are used after model runs to format and present the output and analyses.

5. Remote sensing and other new data sources

5.1 Overview

There is clear complementarity between simulation models and satellite data. First, because remote sensing can contribute to estimating surface agrometeorological variables[2]. Secondly there is now also a tendency to use satellite inputs in crop modelling (Seguin, 1992; Nieuwenhuis et al., 1996; Stott, 1996; Cleevers and van Leeuwen, 1997). In spite of current shortcomings of the proposed methods, there is little doubt that with improving spatial and spectral resolutions, progress will be made in the area of water balance components (soil moisture) and biomass estimations (LAI and conversion efficiencies). An overview of the potential sources of data is shown in Figure 6, according to the concepts presented by Seguin (1992).

Early attempts to use satellite data in crop forecasting focused mainly on Vegetation Indices (VI), i.e. satellite-derived indices that are related to living green biomass. While the qualitative use of VIs has become routine in many countries, their quantitative use in crop yield forecasting has remained disappointing, due to well understood factors. It is suggested that one of the largest potentials for VIs and other satellite inputs such as cloud information lie in their use as auxiliary variables for stratification and zoning, and in area averaging of point data in combination with GIS and geostatistics.

In many circumstances, in particular in many developing countries, fields tend to be small and irregular in size and shape, crops are often mixed, etc. so that the sensors measure essentially a mix of crops and natural vegetation. It is

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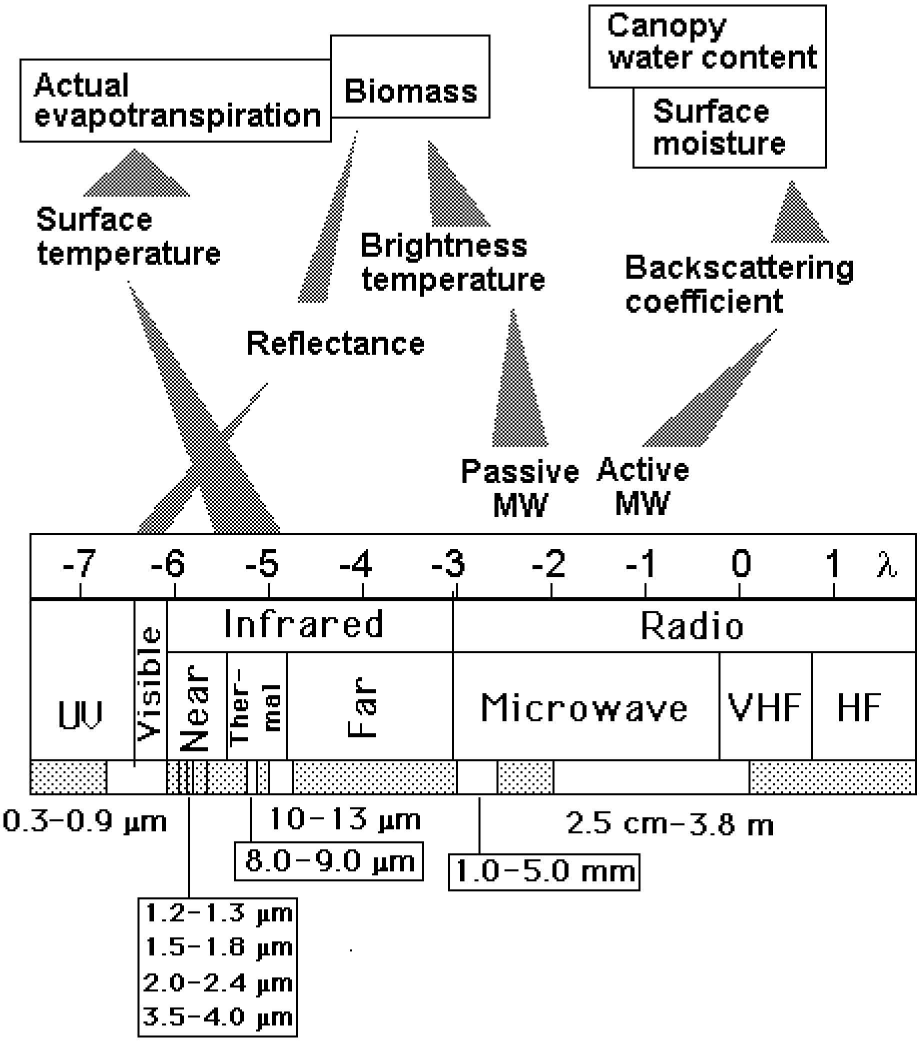
[2] They include rainfall, in combination with ground observations, actual evapotranspiration, leaf temperature.

then generally assumed that crops follow greenness patterns similar to vegetation. This is a reasonable assumption in areas where vegetation shows marked seasonality, for instance in semi-arid areas. Many of the difficulties listed disappear at higher spatial resolutions.

Figure 6: Remote sensing sources of crop weather modelling inputs. λ indicates the exponent of the wavelength in m (- 6 corresponds to a μm, - 2 to a cm, etc.). The bottom line shows the main atmospheric windows, i.e. parts of the spectrum to which there is little absorption in the atmosphere. The absorption is mainly due to CO_2 (thermal infrared) and water vapour. MW stands for microwave. Note that Radar satellites belong to Active MW.

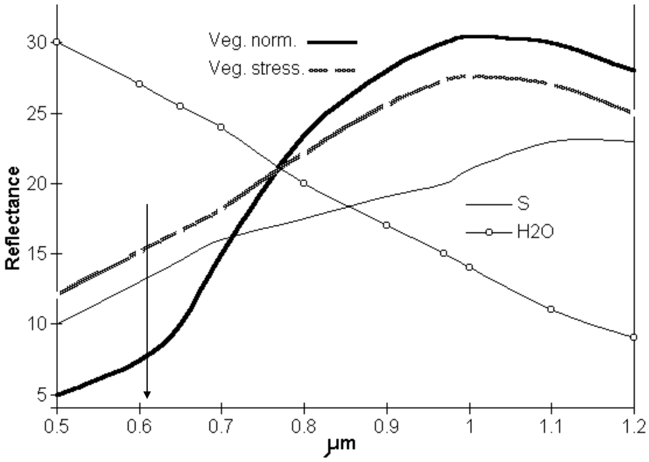


5.2 Vegetation indices

All vegetation indices are based on the fact that plants are green: they reflect a much larger proportion of white sunlight in the green part of the spectrum than in the blue and in the red portions. In fact, plants contain varying proportions of Chlorophyll-a (absorbing mainly the blue between 0.38-0.45 μm and the red around 0.675 μm) and Chlorophyll-b (0.41-0.47 μm and 0.61 μm).

Plants reflect a much larger proportion of light in the near infrared, so that they appear normally very bright when seen through a near infrared filter or sensor. Figure 7 compares the reflectance[3] of different types of surfaces in the red and near infrared.

Figure 7: Reflectance spectrum[4] of stressed vegetation, healthy vegetation (veg. Norm), soil (S) and a water surface H_2O. The arrow indicates the second (red) peak of absorption of chlorophyll.



It is obvious that the spectra of the different surfaces illustrated in figure 7 are characteristic for the surface and constitute their “spectral signature”. In principle, it should thus be easy to identify the surfaces simply by comparing their reflectance.

Things are not so easy, for several reasons. To start with, the spectral signatures are obtained experimentally on the ground under known conditions of irradiance[5]. The radiance measured by satellites has undergone qualitative changes (wavelength) and changes in intensity in the atmosphere. Further, the irradiance varies as well as a function of atmospheric conditions and angle of incidence (which is to say: the time of the day).

Many vegetation indices are thus “normalised” to correct for at least the most obvious atmospheric and soil effects, as in the popular Normalised Difference Vegetation Index (NDVI).

NDVI can be computed whenever red and near infrared reflectance (i.e. reflected radiance) are available, from such satellites as the LANDSAT-TM, SPOT and NOAA-AVHRR.

NDVI can be used to derive phenological information in the absence of ground data. Note that due to the presence of clouds, many readings have to be discarded, which may pose some serious problems in monsoon climates. The operational procedure is, therefore, to use only the maximum values for each pixel during a certain period (for instance ten days). It is therefore also a common practice to smoothen the NDVI curves, often by drawing an envelope around the cloud of observations.

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[3] The reflectance is the percentage of the incident radiation (including light) that is reflected. The word is also sometimes used to indicate the intensity of reflected radiance.

[4] The remote sensing jargon also calls the reflectance spectrum *spectral reflectance*.

[5] Irradiance is the incident radiance, normally as sunlight.

Assuming that crops and natural vegetation are synchronised, planting can be considered to take place at the dekad when NDVI starts increasing again after the dry season, or a fixed number of dekads after D (for instance D+4), or when NDVI crosses a locally determined threshold...

NDVI and other vegetation indices can, of course, be computed at any scale: companies in the USA have started providing very detailed NDVI maps of farms on a subscription basis at the metric scale.

5.3 Surface temperature and evapotranspiration

Because of its relevance for soil water balance calculations, a lot of interest is dedicated to the related subjects of estimation of ETP and surface temperatures using satellite data (Kustas and Norman, 1996; Bastiaansen et al., 1996). The surface temperature T_s is the temperature of the layer of air immediately in contact with the leaf, and T_a is the conventional air temperature measured in a screen.

The interest in the difference between surface and air temperatures goes back to the work on Jackson's CWSI (Crop Water Stress Index; Jackson et al., 1981). The concept of CWSI is very similar to the FAO Water Satisfaction Index (WSI) introduced by Frère and Popov (1979) as a monitoring tool derived from a water balance calculation over the whole cycle[6].

It can be shown (Laguette, 1995, 1997) that, for a given net radiation, there is a direct link between actual evapotranspiration and T_s-T_a, as T_s -T_a is a measure of the sensible heat flux which indicates how much energy is available for evapotranspiration. A large difference indicates reduced evapotranspiration and stomatal closure. A small difference indicates that water supply is adequate and that plants actually evapotranspire. In general, low temperature differences indicate healthy and photosynthesising crops.

5.4 Cold Cloud Duration (CCD)

Cold Cloud Duration (CCD) is determined using the geostationary satellites of the METEOSAT or GMS types. Because low cloud-top temperature thresholds correspond to high elevations, there are relatively very little atmospheric effects to be corrected in CCD when compared with NDVI.

GMS-4 is a Japanese satellite in geostationary orbit over the equator at approximately 140E. The satellite, which covers most of Asia and the western Pacific Ocean, is equipped with the Visible and Infrared Spin Scan Radiometer (VISSR) imaging sensor, which uses the spin motion of the satellite to scan the earth in the East-West direction. GMS begins a North-South scan every hour on the half-hour, with four additional scans daily for wind estimation.

CCD has been used extensively in a food security context to estimate rainfall using various techniques. It is defined, for each pixel and for a given period (usually ten days), as the number of hours during the temperature was below a "cold" temperature threshold around -40°C, which corresponds to convective clouds with high vertical extension assumed to produce rainfall.

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[6] Needless say that the are marked scaling effect when passing from CWSI to WSI.

The technique has been used to estimate rainfall with good results in tropical countries only. For a general introduction to the subject, refer to Bellon and Austin, 1986; Adler and Negri, 1988; Dugdale et al., 1991; Snijders, 1991; Guillot, 1995, Petty and Krajewski, 1996.

Although the relation between the solar radiation reaching the ground and clouds is far from direct (Li et al., 1995), the development of more or less empirical methods is progressing, usually with much better results than with rainfall (Lourens et al., 1995; Wald, 1996; Supit and van Kappel, 1998), among others because the role of clouds in radiation interception is far more direct than in rainfall production. In addition, the methods, once they have been properly calibrated, apply in tropical and temperate countries alike.

The original approach was to try and estimate rainfall based on CCD only, assuming a constant intensity R_i (mm hour^{-1}). Because of the large spatial and temporal variability of R_i, the method is now being replaced by more or less real-time calibration against ground data, using CCD as an auxiliary variable in the spatial interpolation of raingauge measurements.

5.5 Observations by microwave satellites

The use of satellites for the direct estimation of surface moisture involves a number of difficulties (Nemani et al., 1993).

Active microwave (or radar) satellites operating in the centimetric range of wavelengths are relatively unhindered by clouds, and satellites such as ERS-1 and JERS-1 have been providing images of the earth since the early Nineties (Bouman, 1995). Radar is an active sensor in that it emits a bean or energy which is analysed after having been scattered back by the surface: it provides information about the surface, either crop canopy structure or soil surface. Regarding crops, active microwave responds well to row spacing and orientation, and even to leaf orientation. Little operational use has so far been made of the technique because of its large sensitivity to such factors as wind effects on the surface, including leaf orientation.

Much hope is placed in the technique to estimate soil surface moisture directly and possibly crop water content of certain plants. For the estimation of soil moisture, refer to Wagner et al., 1999a, 1999b. Regarding the use of radar remote sensing, often combined with visible imagery, for crop modelling and yield forecasting, see Huete, 1988; Clevers, 1989; Le Toan et al, 1989; van Leeuwen and Clevers, 1994; Clevers, et al., 1994; Bouman, 1995; Doraiswamy and Cook, 1995; Clevers and van Leeuwen, 1996, et Clevers, 1997.

Passive microwave measure the centimetric radiation emitted by the surface. It used to determine the brightness temperature[7], or effective temperature that can be used in biomass estimations.

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[7] Brightness temperature is the temperature of a blackbody radiating the same amount of energy per unit area at the wavelengths under consideration as the observed body.

5.6 Ground-based weather radar

Weather radar, like microwave satellites, operates in the centimetric range. The technique basically measures rainfall intensity within a radius of about 100-Km around the station, sometimes less. Its main advantage is that the spatial distribution of rain over short time intervals can be determined with a significantly better accuracy than with any other technique. As with satellite rainfall estimates, the best results are achieved over relatively long time intervals (days and beyond) after calibration against ground data. A reference quoted by Keane (1998) indicates that in shower conditions, radar calibrated against two raingauges over 1000 Km^2 achieved the same accuracy as 50 raingauges.

5.7 Satellite Enhanced Data Interpolation (SEDI)

The SEDI interpolation method originated in an FAO context, the Harare based Regional Remote Sensing Project. It was originally developed to interpolate rainfall data collected at station level using the additional information provided by METEOSAT CCD. The methods proved powerful and versatile, and it is now regularly used to spatially interpolate other parameters as well (e.g. potential evapotranspiration, crop yields, actual crop evapotranspiration estimates, etc.).

SEDI takes advantage of the correlation between the variable to interpolate and an environmental variable, for instance NDVI/biomass and agricultural yields. One of the ways to approach this is co-kriging, a variant of kriging using one or more auxiliary variable and exploiting both the spatial features of the variable to be interpolated and the correlations between the variable and the auxiliary variables (Bogaert et al., 1995).

Three requirements are a prerequisite for the application of the SEDI method:

- The availability of the parameter to interpolate as *point data* at different geographical locations (e.g. rainfall, potential evapotranspiration, crop yields). In the present case of statistical variables, they were assigned a co-ordinate corresponding to the centre of gravity of the administrative unit;
- The availability of a background parameter in the form of a *regularly spaced grid* (or field) for the same geographical area (e.g. the above-mentioned NDVI variables, altitude).
- A monotonous relation, **at least locally**, between the two parameters (*negative or positive*; Yield/NDVI is positive, temperature/altitude would be negative). A Spearman rank correlation test can reveal whether a relation exists, and how strong this relation is.

6. Conclusions

(1) The leading crop simulation models (CERES, WOFOST, EPIC, and CROPSYST…) are far too complex for Early Warning use. If they are to be used routinely in the **real world**, models should focus on weather and crop variables that are actually available in the **real world**. Such models would also be scale-specific models, i.e. they would have been designed for their use over large areas (provinces, districts) rather than fields.

(2) New tools are needed, and some old tools should be modernised. Researchers should pay more attention to the development of non-parametric and rule based models, because of their simplicity of calibration and use, and low cost. More attention should also be given to efficiency than to fashion: for instance, regression models are not obsolete, but they need being integrated into monitoring systems in combination with the newer tools like GIS, geostatistics, random weather generators...

(3) Efforts must be made to give more attention to new real-time data in crop monitoring and forecasting systems. This includes satellite indicators and weather radar, but also direct (and possibly automatic) measurements on crops and weather at ground stations, or through aircraft remote sensing.

(4) A modular design should be adopted for crop monitoring and crop forecasting systems, as well as a greater inter-compatibility of tools. Users should be in a position to assemble their monitoring and forecasting systems by using building blocks (modules), for instance the root component of CERES, the assimilation block of WOFOST, Leaf-Area Index from the MODIS satellite, etc. The first step should be the harmonisation of data files in the direction of a universal self-documented format.

(5) A new category of models should be developed to assess, at various scales, the effect of extreme weather factors that physically harm plants (frost, sandy wind, and very strong winds), and a better integration of crop, pathogens and competitors. The scale issue takes particular significance in the ambit of EW systems, as other variables they use (socio-economic, nutrition) all come with native scales that must be harmonised.

(6) A serious effort should be made by agrometeorologists and remote sensing experts (including the agencies operating satellites) to publicise the available methods to the experts in national agrometeorological services and food security systems. At the same time, all aspects of accessibility to the new tools and data should be improved. This includes lower cost of products.

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