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Determining the gaps in agricultural information, such as crop phenology, crop moisture status, and drought indices, to improve agrometeorological analyses for agriculture.

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농업기상분석 향상을 위한 농업정보간 격차 도출

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ABSTRACT

Determining those gaps in agricultural and other information to improve agrometeorological analyses for agriculture is a large task. The effective integration of appropriate data systems, including remote sensing systems, with agricultural systems modelling capability is described as a worthy outcome in this endeavour. Data issues, including those associated with data length, quality, maintenance, and archiving remain serious issues to be addressed. The role of remote sensing and geographic information systems in agrometeorology is important and is explored here. The value of simulation models to provide the synthesis for future agrometeorological requirements is further elucidated.

Key words **: information gap, agrometeorological analyses, agricultural system, agrometeorological requirements**

I. INTRODUCTION

Conferences on agrometeorology or agroclimatology are often opened with the observation that agriculture is the most meteorologically and climatology-dependant of all industries. Agroclimatology and agrometeorology are considered somewhat complex composite terms and generally regarded as relatively small and specialised disciplines. Indeed, given the importance of climate to agriculture in a country in WMO RA V such as Australia, it is surprising there is no university department or CSIRO division of agrometeorology or agroclimatology. It is only recently that state and federal departments of agriculture, as distinct from national meteorological agencies, have started employing specialist meteorologists and climatologists working in the field of agriculture. These scientists may be employed within federal and state agricultural research institutions, supporting a policy that is already producing positive results in many regions as these agricultural regions attempt to cope with major meteorological, hydrometeorological, and agricultural droughts and other extreme climatic events.

Nevertheless, in an example of a new emphasis on

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application in agrometeorology, one of the objectives of the first Australian national agricultural meteorological conference in 1996 was: to "*Contribute to an understanding of interactions between weather, climate and agriculture which, when translated into practical systems, will enhance Australia's capacity to positively influence present and future economic scenarios as they relate to agriculture.*"

A decade ago Monteith (1993) posed the question "How can the skills developed in operational, experimental and theoretical aspects of agricultural meteorology be more effectively *integrated* and deployed to make production in systems of agriculture and forestry more reliable, more efficient and above all more equitable in the world at large"

With the above challenges in mind, the purpose of this essay is to explore some of the fundamental features, considered needed to be addressed in agricultural meteorology and climatology. In particular, issues associated with gaps in data, data quality issues, remote sensing and GIS applications and drought assessment measures are explored. Additionally, the ability of models, especially agricultural simulation models, to provide the integration and predictive capability that is needed in agrometeorology applications is reviewed. Some examples of this type of simulation model development in agrometeorology and agroclimatology applications are provided.

1.1. Data issues, with emphasis on 'gaps' in data systems.

In agrometeorological applications, data collected directly in the field are widely considered especially important, because they present the 'ground truth'. Meteorological stations, field data collection (eco-physiological observations, agronomic practices, insect attacks, diseases, soil, etc.) and direct territorial observations are fundamental for the reliability of the whole agrometeorological system. Although considerable effort is placed on quality assurance measures for meteorological station data, it is often suggested those data collected directly from agronomy experiments are generally collected and stored in a number of poorly or minimally documented computer files, with additional information being entered and archived in a variety of field books or diaries. As a result, total data collation and manipulation is generally cumbersome and error-prone, and data loss is frequent (see Maracchi *et. al*, 2000).

It has been argued that in order to attain sustainable agricultural development, a strong emphasis on *integrated* management of all available information is required. Agrometeorology can contribute to the further understanding of the relative importance of each environmental component, especially in optimising the use of natural resources. More recently, this activity has been enhanced and facilitated due to the availability of geographic information systems (GIS), which allow improved management of large quantities of data, including traditional digital maps and databases. The advantages are potentially large, especially for cross-sector interactions and the production of appropriate information for policy and decision-makers in government. Remote sensing may provide the most important informative contribution to GIS, which can provide the basic informative layers in optimal time and space resolutions (from Maracchi *et al*, 2000)..

Nevertheless, it is suggested that only through the availability of real time field data will appropriate and effective crop and other simulation model development be possible with associated provision of appropriate output and subsequent use in decision support systems. As Hansen and Jones (2000) point out 'the availability of input data of adequate quality and spatial coverage is perhaps the most serious practical constraint to application of crop models at regional or larger scales'. This issue also highlights the suitability or otherwise of applying these types of models at a scale different from one for which they were originally developed. Additionally, the high cost of physical measurement at the density required for regional crop and pasture model development normally requires estimation from sparse measurements or more readily available surrogate or proxy data. The situation is exacerbated where spatial databases may be available, there may exist inconsistent boundaries and coverage between soils, meteorological stations, or climate model grid cells (Meinke *et al*,.2000; Hansen and Jones, 2000). Furthermore, crop simulation modelling requires high quality data and adequate representation of the key components and underlying processes involved (Penning de Vries *et al.* 1989). Data requirements in crop simulation modelling are complex and large and include process-related constants such as photosynthetic efficiency, data on partitioning of assimilates and phenological development and other external driving variables. Input data requirements include radiation and temperature and soils data characterising the physiological and morphological processes that determine crop growth defined for a specific model (Lansigan, 2001).

Additionally, while meteorological variables such as air temperature, precipitation, and solar radiation are key input variables needed for simulation models, other (secondary) variables such as wind speed, relative humidity, dewpoint temperature, open pan evaporation, and soil temperature are desirable. Furthermore, a constraint to use of long-term meteorological records concerns the issue of their being mostly placed at airports to serve the aviation industry resulting which can result in a comparative lack of long-term information specific for agricultural environments. To overcome this issue, automatic weather station networks have been established in some countries to serve agricultural needs. However, most automated networks have only been operational for the last 10-15 years, making input into agricultural simulation models sub-optimal and not suitable for long-term simulation studies associated with climate forecast applications (Stone, *et al.* 1993; Hoogenboom, 2000). Hoogenboom notes that the networks, in general, are also not compatible due to differences in instrumentation, sensor height, and data logging.

Virmani (2001) suggests our accepted paradigm of agricultural research has undergone a major revision over recent years. Issues to do with long-term sustainability in agricultural production dominate. It is well recognised that agrometeorological services led by the WMO and many national meteorological agencies are providing an excellent service in systematically collecting, collating, digitizing, and making standard meteorological data available to the agricultural research community'(Virmani, 2001). However, there are now doubts as to whether the data we are currently collecting will meet the future needs of intensifying and sustaining agriculture. Many of our data (such as observations made twice daily by WMO Class A meteorological observatories) in the developing world only provide first approximation data. Virmani argues we need to 'install, maintain, and interlink weather stations'. New installations will have to be established in rural locations. Additionally, in order to sustain future agricultural production near to the ecological potential as possible sophisticated decision-support systems (or, at least, discussion support systems) will need to be increasingly utilised. Extensive information technology tools will have to be developed and employed so that management decisions on-farm and in rural industry can be effectively timed to ensure high and sustained yields.

The transfer of new technology has improved over recent years, due to the availability of long series of satellite data (data archives from NOAA (USA) and Meteor (Russia), containing information for more than 15 years., Additionally, access to archives and the transfer of information, simpler software, and application of INTERNET is facilitating this activity. However, the transfer of the new techniques of processing and interpreting remote sensing data from developed to developing countries is limited by many factors, such as:

- the cost of receiving equipment,
- the restrictive or very difficult access to the archives of satellite images and data, and, notably,
- the shortage of qualified staff. (Maracchi *et al*, 2000).

It is argued that for an agrometeorological service to be effective in using advanced data collection methods such as remote sensing it must have efficient and trained staff. The improvement in technical tools in meteorological observational practice during the last 20 years has created a favourable 'driver' for research and monitoring in many applications of agriculture and forestry. The challenge for research is to develop new systems that can extract appropriate information from remotely sensed data, giving to the final users, near-real-time and appropriate information.(Maracchi, et al, 2000).

It has to be stated here that key international organisations, in particular the WMO, are playing an active role in coordinating efforts connected with receiving, processing, disseminating and using data. For example, WMO's Commission on Basic Systems (CBS) has established a Working Group on SATellites. (WGSAT). The main goal is the development of common working strategies and the improvement of regional and global management capability of satellite data. For this reason, particular emphasis has to be placed on data compatibility and integration between different sources of data. Additionally, the importance of integration of the activity of International Agencies such as the WMO and the FAO needs to be highlighted together with the need for cooperation with national meteorological, climatological, and associated agricultural institutions to facilitate the strengthening of the role of agrometeorology for the service of agriculture.

(Maracchi, *et al*, 2000).

We have summarised below some of the gaps in data systems that are prominent in the literature. These are:

- The need to install, maintain and interlink automatic weather stations, established in the rural regions in well-defined eco-production zones, to meet the future needs for weather data,

A major issue regarding data relates to matching crops to regions. While this may be achieved with use of average climate data there remains the more complex issue of risk management which requires much higher data resolution. Reports and charts of agroclimatic zonation need to be comprehensively applied for integrated regional development of agriculture, to obtain a reasonable distribution of varieties, crops, farming systems, etc. and for the better exploitation of potential productivity. (summarised in Stigter, *et al*, 2000).

- The continued need for a conceptual data base management system as a framework for the future acquisition, maintenance and distribution of climate and agrometeorological data, historical data or observations. This will play a critical role in increased applications of crop models and model-generated output by farmers, consultants and other policy and decision-makers,
- Weather generators for daily rainfall, maximum and minimum temperature and solar radiation are needed, even though the accurate generation of precipitation data, both the occurrence of an event and the amount, remains a difficult task, especially for tropical and sub-tropical regions, .
- a uniform file format needs to be defined to store data for easy exchange between users and developers of crop simulation models,
- A complete and accurate source of rainfall and climate data remains a prerequisite for the efficient crop, pasture, irrigation and other modelling for a wide variety potential uses. While the nature of the individual model may vary, most have the fundamental requirement of a dataset that is complete on a temporal and/or spatial basis. Long-period, high-quality climate and agricultural records are crucial for widespread application of climate information and for prediction services for agricultural planning and operations. This point is reinforced by Stigter et al, (2000) who note the length and quality of the climate and agricultural records are key issues to satisfy the specific requirements of the farming communities,

Jeffrey and colleagues (Jeffrey, *et al.*, 2001) point out that research efforts are hampered by observational records that are typically incomplete, making it difficult to construct a continuous climate record. These data may be recorded for discrete periods, not spanning the entire time period of interest, contain short intermittent periods where data have not been recorded, and contain systematic or random errors. Erroneous data must be removed once detected, a difficult problem in itself.

Additionally, the density of stations and spatial distribution of stations is another inherent problem, especially to those applying models requiring point data. In many applications, the success or accuracy of point simulations can be critically dependent upon the availability of observational data within an acceptable distance of the location under investigation. In remote areas such as Australia the distance to the nearest station can be several hundred kilometres. As a result, the available data may not be representative of the climatology at the desired location.

Additionally, it may be necessary to extract the desired component from a number of background effects. While calibration models are improving and remotely sensed data are becoming widely available, ground-based observational data remain the preferred source of meteorological data. The reconstruction of serially incomplete data records has been much reviewed. This can occur where unbiased statistical analyses may require all datasets to be of equal length and some analyses may impose the additional constraint that all datasets span identical time periods. Climate data typically consist of a large number of stations with limited observation periods. If reliable algorithms are not used to enable reconstruction of long-term records from short-term datasets, a large proportion of the observed data may be rendered useless (Jeffrey *et al*, 2001).

Additional aspects include:

- Improved timeliness, resolution and predictive capability (of central tendencies and extremes) is needed for agrometeorological data, especially data that would have a carry-over effect for wild fisheries,
- better prediction of water temperature from weather and climate data for wild fisheries and

aquaculture is needed,

- Although successes have been obtained in calculating evaporation for irrigation scheduling, improved calculation methods for evaporation under conditions of water deficit are still required,
- Improved quality of crop and agrometeorological data depends on the availability of resources for maintenance of an adequate network. Such resources have been generally insufficient.
- Better use can be made of existing (historic) data, both analysed and not yet analysed, and more effort can be expended on their interpretation.
- Routine measurement of water temperature of inland water bodies used for wild fisheries is recommended,
- good quality historical data are wanted to effectively develop production models in wild fisheries (Kapetsky, *et al.* 2000),
- Alternative means for data collection should be developed by NMHSs in developing countries, under pressure to generate their own funds, using local human resources and training means,
- use of Automatic Weather Stations may 'trade one set of problems for another', because automatic stations need specialised technicians for servicing (Stigter, *et al.* 2000).
- A world-wide policy of maintenance of sufficiently dense agrometeorological networks, especially in tropical and arid zones, is needed and must be complemented by a policy of 'spatialisation' of climatic parameters through multivariate approaches and remote sensing techniques (see, especially, Jagtap, 2000).
- National Meteorological Services and associated agencies should have policies of servicing those areas using agro-ecological frameworks as a basis for siting weather stations in representative locations. (In such policies it should be realised that in most developing countries the agricultural user community has the highest data requirements but the least financial resources),
- in many instances data could be collected *jointly* by the NMS, other scientific institutions, and interested users,
- Agencies that collect and process observational data are also responsible for the installation and the quality control of the observational data. Users accept these data as being accurate and are not aware of the inconsistencies and biases which can occur in such data. While the existence of erroneous data may corrupt the output from a numerical model, these problems may be minimised by rejecting input data that is considered to be (statistically) incorrect. The existence of serially incomplete records is a more serious problem as it can result in the rejection of entire datasets (Jeffrey, *et al.* 2001).
- While numerous techniques for estimating missing data have been implemented it is undesirable that individual researchers should have to expend considerable resources to develop their own databases. Ideally, these problems can be overcome through the development of a single unified archive of quality, digitised, climate data, which is publicly accessible. This would provide the additional benefit of relieving individual workers of the problems associated with generating continuous climate records from sets of intermittent data. (Owens *et al.* 2003; Jeffrey *et al.* 2001).

While extensive archives of observed and gridded datasets are available, these are usually restricted to mean datasets and/or monthly time sets. In particular, in many modelling applications there is a requirement for continuous daily time-step records which are not widely available. Additionally, spatial modelling usually requires access to high-resolution gridded surfaces which are rarely available on a continental scale. Once we have overcome the problems outlined above it is possible to construct a database of observed and interpolated data (Jeffrey, *et al.* 2001).

The datasets described are in use in some countries and have assisted in the development of research, educational, and managerial applications which were previously restricted by the difficulty in obtaining complete and continuous datasets.

The AussieGRASS project (Carter, *et al.* 2000), provides an example where a comprehensive array of agrometeorological data is provided as input to the AussieGRASS model. The model uses a pasture simulation model to estimate various soil, water, and plant parameters. The model uses interpolated surfaces for spatial simulation on a continental scale, and the Patched Point Datasets are used for point modelling at discrete locations. Importantly, applications such as AussieGRASS have also driven the need for database development and they provide the motivation for continued error checking and data analysis.

Additionally, the following measures are proposed:

- There is a need to promote the spirit of unrestricted sharing of and access to information and data that has made meteorology a showcase of international cooperation (Stigter, *et al.* 2000),
- The need to overcome the problem where data from agronomy experiments are collected and stored in a number of minimally documented computer files and data are entered and archived in field books and diaries (Hunt, *et al.* 2001).
- Need to overcome the problems where data manipulation is generally cumbersome and error-prone and data loss is frequent,
- Need to overcome the problem when climate or crop data computer files created may in turn be re-organised and updated to an extent where it becomes unclear as to which files contain original data, why data were changed, and which of the modified data are the most recent,
- The above issues have been recognised in IBSNAT, in using a database for agronomic experiments conducted at different sites highlighted problems of data entry, quality control, and changing requirements for storage and output variables.
- Need remains for central and local databases that facilitate both the searching of information from different experiments and the examination of relationships that may be apparent in a large array of data. Information stemming from agronomic experiments should be stored in a computerised database and managed in a database system. Issues remain regarding the double-handling of data, quality control, changing requirements for storage and output variables (Hunt, *et al.* 2000).

An overriding problem remains in the continuing need for human resources to enter and check data and to maintain and update the management software. This includes,

- The need to provide improvement in the notes and files already used by agronomists together with improving the useability, interchageability, and general understanding of such files,
- The continuing problem with measurements using non-standard units, without a clear indication as to the units and basis of measurement used. (e.g. yield data measured as 'per plot' rather than per unit area basis. The conventions used to define the aspects measured are not adequately documented. For example, leaf area index can be reported without any indication as to whether senescent leaves or parts of leaves have been included, or whether the area of non-lamina structures (e.g. stems and spikes) have been included.
- Yield data quality. Yield data (grain weight and number) may not match the overall yield data, etc. (Hunt *et al.* 2001).

Meteorological data relevant for agriculture also are relevant for inland fisheries and aquaculture, although the relative importance of parameters and their temporal aptness may be different, and thresholds may be dissimilar.(Kapetsky, 2000). Additional aspects include:

- Timeliness, resolution (and predictive capabilities) for agrometeorological data appropriate for inland fisheries need to be improved, providing benefits to inland fisheries and aquaculture. (Geographically synoptic gridded agrometeorological data sets at 1 km resolution should be a short term objective here)(Kapetsky, 2000).

Importantly, the base of data available is often significantly poorer in developing countries than in the developed ones, and better data will probably only become available as a by-product of development (Sivakumar *et al.* 2000).

Recent developments in remote sensing such as soil moisture detection, estimation of evapotranspiration, rainfall etc., constitute new sources of data for many agrometeorological applications. These not only complement ground observations, but also offer new types of data (like those of microwave satellites), provide global coverage and can often be used to improve ground data e.g., in area averaging. However, it is now important to promote the collection and use of these data in operational agrometeorology. Recent advances in the geographical information systems and remote sensing have made the task of integration and mapping of a wide range of databases much easier. Additionally, the determination of agroclimatic production potential using these approaches can help in more efficient agricultural planning. The usefulness of the results of traditional zoning techniques can be enhanced but they need to be complemented by a detailed agroclimatic characterisation, and if the areal extent of conditions is determined with the use of remote sensing (Stigter, *et al.* 2000),

1.2. GIS NEEDS and GAPS.

A geographic information system (GIS) is a computer-assisted system for acquisition, storage, analysis and display of geographic data. GIS technology integrates common database operations such as query and statistical analysis with the unique visualisation and geographic analysis benefits offered by maps (Burrough, 1990) GIS is becoming an essential tool in the effort to understand complex processes at different scales: local, regional and global. In GIS, the information coming from different disciplines and sources, such as traditional or digital maps, databases and remote sensing, can be combined in models that simulate the behaviour of complex systems. Data input can be obtained by means of direct digitalisation, scanning or acquisition from compatible sources.

The possibility to transform the data into different formats, allows fast interaction between different informative layers. For the agronomic and natural components, in agrometeorology these tools have taken the name of land information systems (LIS). In both GIS and LIS the key components are the same (hardware, software, data, techniques and technicians), but in relationship to the information that is required, their relative importance varies. In particular, LISs requires a series of very detailed information on the environmental elements, such as meteorological parameters, vegetation, soil and water. The final product of a LIS, is often the result of a combination of numerous complex informative layers, whose precision is fundamental for the reliability of the whole system. This technology allows the contemporary updating of geographical data producing rapid adaptation to real conditions and obtaining results in near real-time. The system requires preliminary basic information that, in the agrometeorological sector, is often supplied by historical archives of different disciplines such as geography, meteorology, climatology and agronomy.

In agrometeorological applications, data collected directly in the field remain fundamental because they present 'ground-truth'. Meteorological stations, field data collection (eco-physiological observations, agronomic practices, insect attacks, diseases, soil, etc.) and direct observations are fundamental to all possible agrometeorological GIS applications. All these sources provide reality of the territory and the condition of the elements that it is composed of. These data can be used directly or after further treatment. Remote sensing provides spatial coverage by measurement of reflected and emitted electromagnetic radiation, across a wide range of wavebands, from the earths surface and surrounding atmosphere.

There is continued need to improve satellite system utilisation. There is the prospect of substantially improved transfer to communities around the world via rapidly evolving global and regional communications networks. This will allow improved access to satellite data and services.

While rainfall can be measured relatively easily and there are a number of algorithms that create interpolated 'rainfall surfaces' from point data identifying more precisely where, when, and how much rain has fallen in a specified time period is not generally available on a daily basis. This problem especially applies to data sparse regions such as Australia, especially in the north and centre of the continent. The spatial gaps in the data have caused immense difficulties in accurately monitoring and forecasting areas susceptible to drought. One way to avoid these difficulties is to use a regular information source from which rainfall in these outback areas can be inferred with accuracy. Remotely sensed data collected from satellites is the most cost effective and practical method of doing this. Over the last 20 years, much work has gone into investigating the use of infrared (IR) satellite data from both the polar orbiting US National Oceanographic and Atmospheric Administration (NOAA) satellites, and the geostationary meteorological satellites.

The most important requirement of such an approach is that it is able to distinguish precipitation from non-precipitation clouds and to pinpoint areas where precipitation is heaviest. In the past, limitations in computing power relative to the quantity of data and the learning needed to run the complex software necessary for manipulating them, have made it difficult to create a methodology that could be used by non-specialists to obtain rainfall information. However, simple enhancement of GMS IR satellite data, and the manipulation of these data in a GIS can cover the above issues, allow some predictive capabilities, and enable the production of an output such as a colour map indicating key regions of excessively wet or dry conditions (Bryceson, 1994).

There is continued need to improve systematically the utilisation of satellite systems with emphasis on improving utilisation in the developing countries.

There is continued need to:

- focus on the needs of developing countries;
- improve access to satellite data through increased effectiveness in the distribution of satellite system data and products at major hubs, in particular those maintained by the satellite operators, WMO WMC's, RSMCs and other entities as appropriate. (Maracchi, *et al.* 2000).

In developing countries, GIS use can be promoted through transfer of technologies and using information from developed countries. This requires some generalisation of the knowledge and studies carried out in other regions. Moreover, frequently in developing countries, data used for the production of the informative layers may be unreliable or lacking. Additionally, the models used in these systems are the results of studies and projects, developed for different scales (Maracchi, *et al.* 2000).

The general philosophy of projects, finalised to produce GIS, is to develop and produce more and more complex and integrated systems, to satisfy the needs of users. However, in developing countries, the approach may need to be quite different, resulting in a first phase that produces sufficiently simple systems, which answer specific problems, eventually completing the different informative layers and to create a fully operative GIS. An example of preliminary information system to country scale is given by the SISP (Integrated information system for monitoring cropping season by meteorological and satellite data), developed to allow the monitoring of the cropping season and to provide an early warning system with useful information about evolution of crop conditions (Di Chiara and Maracchi,1994)

The existence of new tools is provided to reinforce the use of agrometeorology and to increase its applications both in developed and developing countries and is based on the strengthening of this use of GIS and remote sensing in the national services, research and training. To reach this objective there are several gaps:

- greater visibility of agrometeorology at both national and international level,
- a larger participation with international programs,
- better integration of agricultural science, geography, meteorology and climatology,
- the reinforcement of training in these new fields of agrometeorology and GIS,
- the promotion of specialised software in agrometeorology and GIS,

Although satellite-derived imagery has been shown to be useful in broad-scale spatial assessment of green cover (Dudgeon, *et al.* 1990), it has inherent limitations in providing a total solution for drought and rangeland monitoring. Better assessments of the quantity and quality of biomass are needed, as well as consideration of herbivore densities and future climate scenarios. Similarly, rainfall analyses do not necessarily reflect the quantity and quality of grasses or pasture that will be present on the ground. The agro-political focus of drought is now shifting to self reliance in some countries and this necessitates putting any current climatic or agro-climatic situation into a probabilistic context within the last 120 years. Governments may not wish to intervene in terms of drought recovery aid with a 1 in 5 year dry period but may well respond to widespread 1 in 20 year drought events.

To overcome these problems the Normalised Difference Vegetation Index (NDVI) form the NOAA weather satellite has been used operationally for assessing green cover across the State of Queensland in Australia (Figure 1). Mean/variance relationships calculated from NOAA imagery has been used for mapping tree cover inputs to the model. Queensland still has a high level of tree cover which confounds the pasture component of the signal. Green cover is also measured across the State by comparing 'ground-truthing' using a survey team. Unfortunately, there is still not a standard archive in Australia of the full series of NOAA imagery. Archives held by different research groups cover different areas of the continent and lack a rigorous calibration for sensor drift and atmospheric condition (Brook and Carter, 1994).

The above information in figure 2 provides an example of the value of integrating remote sensing data with an understanding of the underlying agrometeorological processes, especially related to plant species growth. Further integration is possible when forecasts of potential grass production are made. This is achieved when current soil moisture data and actual rainfall recorded to date is combined with a climate forecast model and pasture production simulation model. An example of this type of output is provided in figure 3.

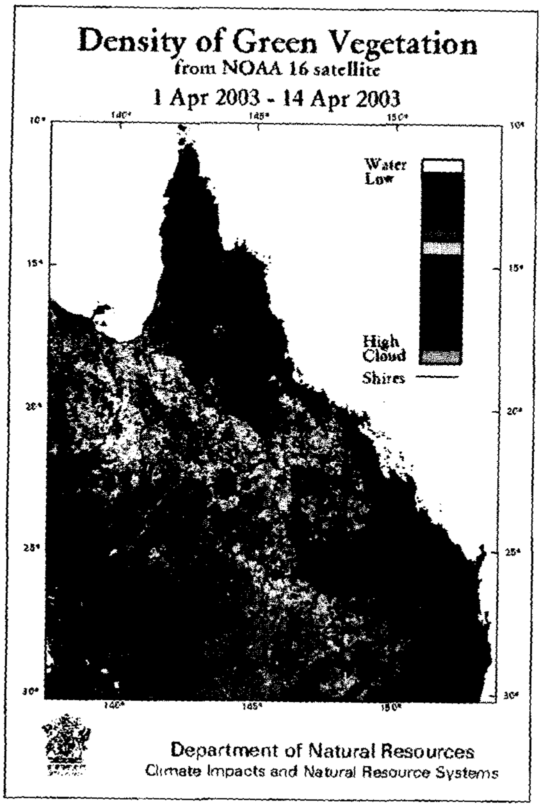

Fig. 1. Example of application of remote sensing data in assessment of green vegetation coverage in Queensland, Australia, April 2003.

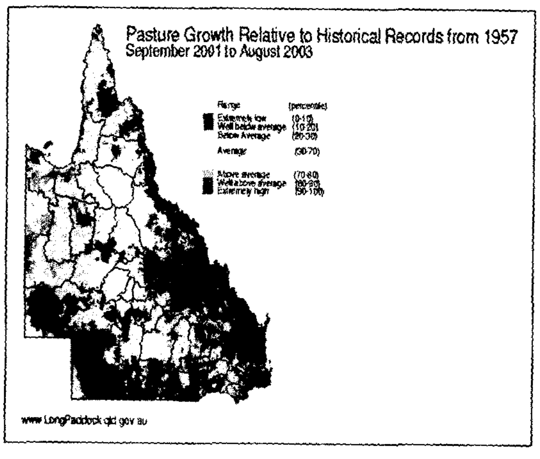

Fig. 2. Example of integrated assessment of pasture growth in Queensland, Australia, using remote sensing (NOAA imagery), 'ground-truthing' and statistical analysis to provide policy makers and rural industry with relevant agrometeorological information.

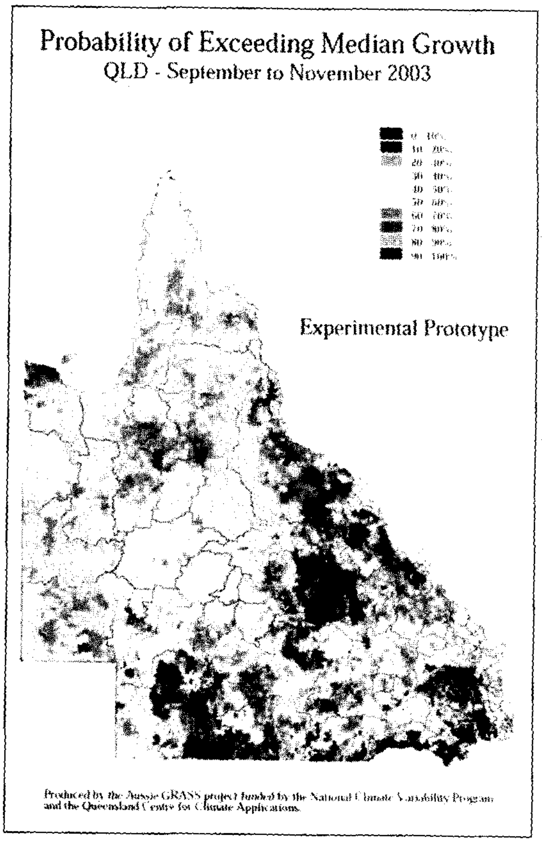

Fig. 3. Example of the value of an integrated approach in agrometeorology where real-time data (rainfall, temperature, soil moisture status) is integrated with a simulation model and a climate forecast model (provides daily time steps of forecast rainfall, maximum and minimum temperature, evaporation, radiation).

2. AGRICULTURAL SIMULATION MODEL DEVELOPMENT

Jagtap and colleagues present 23 major applications of crop models in sub-Saharan Africa and a description of some of these models. Conventional empirical approaches are considered inadequate for addressing the complexity of the interaction between global climate, regional weather variability, decision making, agricultural productivity and economic responses. Appropriate models must be further developed to continue opportunities and challenges for agrometeorologists and others to assist in solving the complex agricultural problems in these areas (Stigter, *et al.* 2000).

'Positive and negative' extremes in successes with the application of modelling in answering needs in agricultural information have been shown by Monteith. Monteith makes two warnings (i) on the compatibility of sources of empirical and other information that is entered into the models; (ii) on the appropriate calculation of errors as part of the model output, including those caused by input parameters, that are not devoid of errors. Nevertheless, there is a need for more active applications of models for phenology, yield forecasting and related subjects are considered a priority area. Additionally, there is an urgent need for the development and the validation of models for crop-pest management systems and in guiding production and including the influence of diseases, weeds, and various technology measures and economic factors. Stigter and colleagues add that the application of crop models towards understanding the effects of climate variability and climate change is a most effective means of applying the tools of agrometeorology (Stigter, *et al.* 2000).

However, a large gap remains in identifying means of combining General Circulation Models and crop simulation models (most effort is made on connecting statistical climate forecast models with crop simulation models). If this could be achieved the outcomes would provide a good scientific approach to study the impact of climate variability and/or change on agricultural production and on the world food supply (Stigter, *et al.* 2000).

Since the availability of micro-computers in the 1970s there has been an abundance of crop models developed. Reviews regarding the efficacy of crop models show slight variants on categories of simulation modelling and a range of warnings and directions for appropriate form and function of simulation modelling. An overview of current views on simulation models has been provided in a series of four papers in the *Agronomy Journal* (Passioura 1996, Monteith 1996, Sinclair and Seligman 1996 and Boote *et al.* 1996). Other recent reviews have emphasised work conducted in North America (Whisler 1986, Ritchie 1991), India (Monteith and Virmani 1991) Australia (Carberrry 1994, Stapper 1994, Hook 1997) and some of the Dutch and Australian tradition (Meinke 1996).

Although new simulation models will continue to be built, the field appears relatively stable. Nix (1985) argued that the demands of reality and practicality had led to a convergence in the structure and function of crop systems models. Carberry (1994) noted that the prediction accuracy of parameters such as yield in current models (R^2 of 0.63 to 0.88) was a significant improvement over those developed prior to the 1980s. However, due to sampling error in experimental data used to build and test models, future models were unlikely to achieve greater accuracy than the current systems. Sinclair and Seligman (1996) suggested that crop simulation modelling was now entering a long and productive mature phase.

The case for use of simulation models is often contrasted with the case for a dominant strategy of agricultural research based on field experiments. Nix (1985) was critical of studies which showed *"statistical differentiation of treatment effects on specific crops and cultures on specific soils at specific locations in specific seasons"*. Similarly Williams (1994) referred to the ability of models to overcome the *tyranny of site and season.* McCown *et al.* (1991b) pointed out that field experimentation had dominated not only research but also extension in modern agriculture. They argued that the complexity of management alternatives and a variable climate led to limitations in field experimentation which simulation modelling could help overcome.

Simulate to understand or simulate to predict?

There are two main reasons for wanting to add complexity to crop models; as a means of expressing and improving understanding of the system or as a guide to appropriate action which will improve the system. Passioura (1996) argued that there had been confusion between scientific (understanding farming systems) and engineering (guide future action) functions for models.

In Australia there has been a strong emphasis on the application of agricultural production and simulation models to guide farmer and policy action (Woodruff 1992, Foale and Carberry 1996, McCown *et al.* 1993, 1998, Hammer and Nicholls 1996). This application is seen as at the forefront of such developments in the world (Shorter 1996). However, Carberry (1994) expressed dismay that of 283 publications on maize models since 1986, 83% defined, calibrated or validated functions in models, only 17% had any management focus.

Hammer *et al.* (1996) questioned Passioura's (1996) distinction between models having either a scientific role of understanding or an engineering role of prediction. They doubted that the science modeller who refused the challenge to predict really understood and conversely whether the engineering modeller could really predict if he or she didn't understand but had to tune the model for every novel situation. They asserted that the real challenge was to combine the science and the engineering by building crop models based on sound agronomic and physiological principles and an ability to predict performance well.

Selvaraju and colleagues (Selvaraju, *et al.* 2004) has shown the value of the application of integrated climate forecasting systems with crop models in southern India. The main value of this work is that agrometeorological and agroclimatological analyses are significantly improved once climate forecast systems and cropping simulation systems are combined. Selvaraju was able to show that analyses leading strategic crop choice decisions (sorghum and groundnut) could be greatly improved through use of simulation models. Important gaps in understanding crop adjustment practices in India could be addressed through the use of new technologies in crop simulation modelling and climate forecasting.

The main role for simulation modelling in agroclimatolgy has been to produce a series of probability distributions for different management options that can then be compared. In his review of agroclimatic risk management, Angus (1991) referred to Knight's (1921) distinction between risk and uncertainty. Implicit in his presentation and others at the same conference was the role of science in taking farmers' uncertainty about the outcome of a decision and providing quantification of that uncertainty as risk. Science can deliver risk assessment through simulation modelling.

3. CONCLUSIONS AND FURTHER WORK

Despite the major advances being made in remote sensing and in crop modelling and other scientific measures, in agrometeorological applications, data collected directly in the field are still regarded as providing fundamental input to our understanding of agrometeorology. However, as Maracchi points out, 'meteorological stations, field data collection (eco-physiological observations, agronomic practices, insect attacks, diseases, soil, etc.) and direct territorial observations are fundamental for the reliability of the entire agrometeorological system.'

Additionally, it must be recognised that the availability of input data of adequate quality and spatial coverage is a serious constraint to the development of 'new technology' simulation models. Simulation models are increasingly being applied in assessments of potential crop and pasture growth and for indication of reduction in yield in times of drought. This type information is increasingly being sought by governments in order to provide drought relief aid and development of similar policy measures. However, as the value of agrometeorology and agroclimatological analyses are now increasingly being recognised by governments and industry, questions are being raised regarding the suitability of applying these types of models at different scales from one for which they were originally developed. Additionally, the legitimacy of the model inputs and outputs can be seriously questions when matters of many millions in financial aid for drought and famine relief are being considered.

Unfortunately, the high cost of physical measurement at the density required for regional model development normally necessitates estimation from sparse measurements or more readily available, less reliable surrogate data. More than ever before there is need for the agrometeorological community to provide evidence of a holistic approach to key issues. It is suggested the *integration* of the relevant disciplines remains the key to the advancement of agrometeorology. Scientifically valid and accurate simulation modelling is one example of the effectiveness of an integrated approach in agrometeorology. In simulation modelling the value of appropriate and lengthy quality data bases in model development is paramount. Furthermore, the value of remotely sensed data and geographic information systems is immediately apparent in development of tools and products that will provide real value to government policy and industry development. The challenge remains in development of appropriate international projects and programs that will enhance this development.

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