WORLD METEOROLOGICAL ORGANIZATION

COMMISSION FOR AGRICULTURAL METEOROLOGY

CAgM Report No. 92

THE IMPACTS OF AGROMETEOROLOGICAL APPLICATIONS FOR SUSTAINABLE MANAGEMENT OF FARMING, FORESTRY AND LIVESTOCK SYSTEMS

Final Report of the CAgM Working Group

Submitted by

A. Kleschenko (Chairman), L. Grom, M. Ndiaye, and R. Stefanski

WMO/TD No. 1175

Geneva, Switzerland

March 2004

CONTENTS

FOREWORD

During the 12th Session of CAgM held in Accra, Ghana, February 1999, a Working Group on “The impacts of agrometeorological applications for sustainable management of farming systems, forestry and livestock” was established. The group was in turn composed of six rapporteurs from different countries. Three members left due to different reasons and one new member (USA) was introduced. The WG Chairman prepared a draft report with the individual submissions from each rapporteur and submitted it to all group members. A joint meeting of WG members in September 2000 (four WG members were present) in Geneva reviewed the submissions and a time-table of further work on the final report was prepared.

A. Kleschenko

INTRODUCTION

Sustainable development was widely and comprehensively discussed at the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro, Brazil in June 1992. Considering the exceptional importance of sustainable development for mankind, the WMO CAgM determined some of the priorities for agrometeorologists to address sustainable agriculture. These include:

- the use of agrometeorological applications for sustainable management of farming, forestry and livestock;
- examples of potential application of geographic information systems and agrometeorological zonation in operative agrometeorology;
- examples of the potential impact of agrometeorological applications.

In the first version of the report it was planned to consider all of the above problems as applied to various regions. Because of the WG members left, however, materials on the following problems were presented:

- a chapter on solving the above problems in forestry (prepared by Mr. R. Stefanski);
- a chapter on solving the above problems in the Central Asia region (prepared by Mrs. L. Grom);
- a chapter on solving the above problems in farming systems (prepared by Prof. A. D. Kleschenko).

CHAPTER 1

AGROMETEOROLOGICAL APPLICATIONS FOR SUSTAINABLE MANAGEMENT OF FARMING SYSTEMS

by Prof. A. Kleschenko
National Institute on Agricultural Meteorology
Hydrometeorological Service of Russia
E-mail: cxm@meteo.ru

1.1 INTRODUCTION

Problems related to sustainable development in the world were widely and comprehensively discussed at the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro, Brazil in June 1992. A global plan of action aimed at the application of high environmental quality and health economy requirements for everybody was developed.

Practically during the whole period of its development, mankind was concerned with the maximum profit making but not with sustainable development. This problem is especially pressing for agriculture because the dramatic increase in world population and decrease in arable land, especially in developing countries, increases the load on natural resources. According to Baier et al (1999), the concept of sustainable agriculture involves ecological, economic and social problems. In this case, climate may be of great importance. Along with soil and plant (animal) material, climate is the essential component of agricultural production. Climate is a renewable resource that changes in time and space therefore its knowledge allows to use other natural resources more effectively and, mainly, to develop the optimum load on natural resources.

The following problems of sustainability were regarded in that light at the conference (Baier et al, 1999):

- research into an improved understanding natural climate variability and anthropogenic climate change, including biospheric processes influencing climate;
- enhancing the protection, sustainable management and conservation of all forests, and greening of degraded areas, through forest rehabilitation, afforestation, reforestation and other rehabilitative means;
- improvement and strengthening of meteorological and hydrological networks and monitoring systems to support data collection for research into the interactions between climate, drought and desertification and for assessment of their socio-economic impacts;
- strengthening the knowledge base and developing information and monitoring systems for regions prone to desertification and drought and other natural disasters, i.e. erosion, floods, landslides, earthquakes, snow avalanches;
- conservation of biological diversity;
- protection of the quality and supply of freshwater resources;
- application of integrated approaches to the development, management and use of water resources.

Proceeding from a global plan of action adopted at the conference, Moiseev (1994) states that sustainable development in any country should be based on the following principles:

- a principle of "goods succession", i.e. the subsequent generations should have equal potentials for using the planet's resources with the present-day generation;
- a principle of "potential equality", i.e. all countries have the right to use natural resources proportionally to population with the observance of any limiting standards (including chemical, radioactive and biological) of environmental pollution.

Further, Moiseev considers that a conceptual program of sustainable development should be based on a program of fundamental research aimed at studying the biosphere as a system and, first of all, at studying conditions sufficient to support quasi-equilibrium in the biosphere during a certain time period, i.e. the period of several generations.

A program should also foresee development of the concept of transition from administrative-territorial to natural-social-territorial structurization which allows to increase the management resource and to rely on natural organization of biospheric systems. In this case it should be remembered that the structural subdivisions of biosphere are not state borders and administrative-territorial units but natural ecological landscapes.

According to the United Nations decision, all countries should present their program of sustainable development by 2002.

1.2 SUSTAINABLE MANAGEMENT OF FARMING SYSTEMS FROM THE POINT OF VIEW OF AGROMETEOROLOGY

As Sivakumar (2000) explains, with the loss of the most productive agricultural lands (due to the expansion of residential and industrial sectors) and decrease in the growth rates of irrigation, 2/3 of the future growth of agricultural production will result from increasing crop yields. More and more technical efforts are required to support this level of production. So when solving one of the aspects of sustainability, i.e. increase in the crop yield productivity, as before, the problem of soil depletion, anthropogenic loads and contamination cannot be solved.

Grain harvest per person showed a continuous decline from 1984 onwards. The 1995 harvest of 293 kg per person is 15 percent below the peak of 346 kg in 1984 (Brown et al, 1996).

It is necessary to also consider the process of soil degradation in developing countries and countries with transitional economies. In Russia, for example, disturbances in the basic natural agrolandscape component, i.e. soil, may be summarized as follows: the acid-base balance is broken and there is dehumification and destructurization, enhanced erosion, salting, alkalinization and pasture degradation. These processes result in the loss of soil fertility and agricultural biological diversity. In the middle of 1990s in Russia, more than 20% of agricultural lands were eroding, now 44% of lands are erosion-dangerous, about 20% salted, 19% swamped, and degradation is observed at about 50% of haylands and pastures. The negative processes above refer to functioning agricultural landscapes only. Great land areas are idle and fallow. Biological diversity is being reduced here, soil properties are comparable to the zonal ones and this can be considered as a favourable process. This positive effect, however, is too insignificant to compensate the negative consequences of a general tendency to degradation.

It is now well understood that the food needs of future populations have to be largely met from increasing the productivity per hectare. Cereal output per hectare in the developed countries is high, but it is achieved using high levels of commercial energy. Currently, the production of 1 kg of rice needs 4700 litres of water (Lampe, 1996). Farmers in the developing countries, with limited means at their disposal, cannot be expected to achieve higher per hectare productivity by simulating the example of high energy use of the developed countries.

There is an urgent need for a transition from chemical- and machinery-intensive to knowledge- and labour-intensive farming technologies (Swaninathan, 1996).

Despite the high importance of intensive chemical and technical equipping of the agroindustrial complex and land reclamation, the possibility of agriculture recovery is not high. It is especially true for countries with unfavourable soil-climate and weather conditions, for example Russia, where insufficient heat and water supplies are observed in most of farming areas. In countries with a traditionally high level of agriculture, the crop yield variability is 50-80% dependent on climate and weather changes and ecological and biological stress drops with its increase. The variability of crop yields are mostly determined by weather and not by agrotechnical factors. The less favourable weather conditions, the higher is the fraction of their impact on crop yields and quality variations.

It is known that the more unfavourable the soil-climate and weather conditions, then to a greater extent non-adaptation in crop and variety selection, their localization, application of technical means, agroecosystem and agrolandscape designing decreases the production value and quality and increases the danger of environment pollution and destruction. The world market situation and spontaneity played and plays now a negative part.

There are many definitions of sustainable agriculture, most specify (Ford and Kanemasu, 1997) that sustainable agriculture systems exhibit the following characteristics:

- provides for the long-term maintenance of agricultural productivity;
- maintains the natural resource base;
- provides adequate long-term economic returns to agricultural producers;
- protects human health;
- provides for the needs of rural and urban communities in a manner consistent with indigenous social fabric and goals.

Regional systems of sustainable agricultural production oriented to the combination of high production, ecological stability and environmental control are now being developed in Europe and all over the world (Zhuchenko, 2001; Zellei, 2001; Gatzweiler et al, 2001; Wiren-Lehr, 2001).

This regional system developed for Russia (Zhuchenko, 2001) and much different from other systems includes the following components:

- differentiated use of the potential of cultivated plant types and varieties, natural and anthropogenic factors;
- agroecological macro-, meso- and microzonation of territories and adaptive agriculture;
- designing of highly productive and ecologically stable agrolandscapes based on mechanisms of ecological self-regulation;
- adaptive selection, strain test and seed farming;
- agroecosystem pest, disease and weed control by regulating their population;
- development of computer databases and information technologies with different territorial and space-time resolution.

Proceeding from decisions of the United Nations Conference on Environment and Development (UNCED, Rio de Janeiro, Brazil 1992), the following trends of agrometeorology essential for sustainable agriculture are highlighted (Sivakumar et al, 2000):

- improvement and strengthening of agrometeorological networks;

- development of new sources of data for operational agrometeorology;
- improved understanding of natural climate variability;
- promotion and use of seasonal to inter-annual climate forecasts;
- establishment and/or strengthening of early warning and monitoring systems;
- promotion of geographical information systems and remote sensing applications and agroecological zoning for sustainable management of farming systems, forestry and livestock;
- use of improved methods, procedures and techniques for the dissemination of agrometeorological information;
- development of agrometeorological adaptation strategies to climate variability and climate change;
- mitigation of the effects of climate change;
- more active applications of models for phenology, yield forecasting etc.;
- active promotion of tactical applications such as response farming at the field level;
- promoting a better understanding of the interactions between climate and biological diversity.

Practical realization of the above trends in a regional farming system should be based on the information about soil-climate and weather resources for the specific territory, farm or farmer. A better understanding of the interactions between physical, climatic (weather), and biological components is necessary to understand many ecological consequences of agricultural development. This understanding will further enhance the role of agricultural meteorology.

The greatest impact of hydrometeorological support on management decisions contributing to sustainable farming is made when using data on extreme events and agrometeorological phenomena.

It is clear that activities of practically all branches of an economy depend on environmental conditions. The degree of dependence, however, is variable. Agriculture is among the 5 or 6 basic Russian Federation industries which account for a large portion of losses which can be prevented as a result of timely and comprehensive application of hydrometeorological information and proper management decision-making.

According to Bedritsky (1994), Russian agriculture is most “open” to the external environment and, hence, it is the one sector of the Russian economy that is the most impacted by hydrometeorological factors (60% of the total damage for all economic sectors due to natural hydrometeorological phenomena). Other economic sectors such as power engineering, transport and construction activity account for almost equal levels of damage (6.8 to 9%). In other countries this situation seems to change and remain steady only in the following: agriculture is much influenced by climatic and weather factors.

Speaking about sustainable management of agrometeorological applications in farming systems, forestry and livestock, it should be remembered that any management decision, in addition to increasing sustainability, must pursue the potential benefits (including economic) of agrometeorological applications. Therefore in our opinion research in the framework of this problem must be carried out in the following three areas.

First, theoretical studies on sustainable development and the development of economic-agroecological models of optimal decision making (both on sustainability and efficiency) based on hydrometeorological information.

Second, applied studies including most of the developments concerned with the application of agroclimatic information and agrometeorological forecasts in different branches of farming.

Third, selection and development of priority systems for strategic support in agrometeorological service (Stigter, 1999) with the substantiation and assessment of benefits of hydrometeorological data application in farming systems, forestry and livestock taking into account the response of different applications to weather conditions, climate, and loss associated with adverse weather conditions.

1.3 MATHEMATICAL INTERPRETATION OF SUSTAINABILITY PROBLEM AND ECONOMICO-AGROECOLOGICAL MODELS OF OPTIMAL DECISION-MAKING

The first part of this section was prepared using Moiseev (1994) and Tarko's (1995) papers' and materials from the Potsdam Institute for Climate Impact research http://www.pik-potsdam.de.

Human interventions, such as the continuing release of fossil-fuel combustion products into the atmosphere or the fragmentation of vegetation play a significant role in the Earth system. We are currently altering the character of the Earth at an increasing rate, and the present dynamic variability of the Earth system itself may be endangered. During the last 10,000 years the climate has been relatively stable compared with the 100,000 years preceding them. The development of agriculture and the simultaneous growth of civilizations during this phase of climate stability is probably not coincidental. An important and exciting question is therefore: Could the Earth system return to a more unstable mode if the concentration of greenhouse gases in the atmosphere continues to increase?

The problem of Earth system stability includes: 1) the land biosphere and its feedbacks to the atmosphere, 2) the interactions between all major components of the Earth system (atmosphere, ocean, biosphere, ice masses) and 3) the long-term evolutionary dynamics of the geophysical Earth system. The dynamics of – and between – the Earth's subsystems require an integrated analysis of the fully coupled system. Due to the non-linear synergisms between the sub-systems, the response of the entire Earth system to external perturbation drastically differs from the sum of the responses of the individual subsystems or a combination of a few of them.

In a coupled Earth-system model, the land biosphere represents a significant element of non-linear behaviour. Results obtained with simplified models have shown that the biosphere could be capable of showing either considerable inertia due to slow vegetation responses or, alternatively, rapid "pulses" due to fast mobilization of carbon from the land to the atmosphere (fire). In addition, biological processes (e.g. the response of plant productivity to increased atmospheric CO_2) could offset, for example, decreases in growth that would be expected to occur if only a warming trend was considered. Responses of the biosphere to changing climate will also be different regionally, just as scenarios of changing temperature and rainfall differ from place to place – a spatially explicit model is therefore imperative for the study of these processes. The spatial and temporal dynamics of the biosphere have strong implications for the overall system, and hence for the future of a sustainable Earth, for several reasons. Firstly, the time constants of carbon pools on land, most of which are connected to vegetation or the soil, span a wide range from minutes to many centuries. This is due to rapid (mostly light-driven) changes in the photosynthesis in plants on the one hand and the relatively slow build-up of biomass in most ecosystems and the slow to very slow decay of organic matter in the soil on the other. In consequences, one may ask whether ecosystems ever can be in true equilibrium with climate. The disequilibrium is even more crucial in times of rapid changes in climate and CO_2 since it prohibits the estimation of carbon pools from present climate and demands a full account of system history.

A second cause for concern are the physical feed-backs between land vegetation and atmospheric circulation. Vegetation structure directly affects most climate-relevant properties of the land surface, and it does so differently, depending on the time of the year, the stage of vegetation development or the local land use. Overall, the physical and biogeochemical feedbacks of vegetation in the earth system may therefore accelerate or retard any general trends, and the balance between these may be different in different regions.

Le-Chatelie's principle plays an important role in the analysis of feedback mechanisms. This principle is formulated as follows: the external impact, disturbing the system from equilibrium, stimulates processes which tend to mitigate the results of this impact. This principle in different disciplines is treated differently. In statistical physics the principle is considered for a thermodynamically closed system in equilibrium where the rule of maximum entropy is fulfilled. Biosphere or any its part in statistical physics is not a closed system. Therefore, there is no necessity to fulfil Le-Chatelie's principle in the above sense. It may be useful, however, not as a "rule" but as a property, the fulfillment or non-fulfilment of which characterizes the ability of biosphere to mitigate the impact.

Calculations performed by Tarko with the simplest climate models have shown that at present Le-Chatelie's principle with respect to CO_2 is fulfilled and will be fulfilled up to the 22nd century. If to assume that the annual plant production of land decreases with the 1.5 fold atmospheric CO_2 content increase (this dependence was found in some laboratory experiments), Le-Chatelie's principle is not fulfilled and land will be the source of CO_2 in 2050-2100.

A very interesting result was obtained by Moiseev (1994) who showed that feed-back mechanisms which maintain the stability of a system able to self-reproduction appear under the action of purely stochastic factors. He showed that inaccurate reproduction (reduplication) not only forms a feedback mechanism, but can also transform the totality of individual components into a certain system of interrelated elements when changes in one of them affects the others. A particular example of these inaccuracies are mutations in biological systems. Mathematical calculations in more detail are given by Moiseev (1994).

The above considerations are the base for developing a new class of models – Dynamic Global Vegetation Models (DGVM). DGVMs are developed against the background of changing conditions. These are currently considered in three ways (all of which may occur simultaneously): 1) changing physical climate; 2) changing atmospheric CO_2 concentration and nitrogen deposition; and 3) changing disturbance due to human land use. Estimates of vegetation response to changing climate and carbon dioxide are now made using DGVMs, although one of the most crucial components is still in its infancy: the dynamics of human land use.

DGVM applications recognize that the actual response of the biosphere to some change is necessarily specific to a particular region. In fire-prone ecosystems such as savannas or boreal forests small changes in the soil-moisture balance may affect fire frequency just enough to change the composition and therefore structure of the ecosystem quite rapidly. Since such changes mainly depend on the moisture balance, and since plant response to changing moisture is affected by atmospheric carbon dioxide, we are left with a major uncertainty for large-scale predictions of the outcome of such a change – therefore a DGVM will need to be run at a large number of locations.

In ecosystems such as the wet evergreen rain forests the main disturbance will most likely continue to be land use rather than climate change. Here, the DGVM only simulates direct results of external forcing, i.e. the flux of carbon from destroyed vegetation to the atmosphere, with no particular attention to plant population processes. In yet another type of ecosystem, the Arctic tundra, migration (the horizontal displacement of plant seeds or other propagules) needs to be simulated before we can estimate the change of the land surface.

As to the development of economic-agroecological models of decision-making based on agrometeorological information, numerous research has been done in this field (Fedoseev, 1979; Zhukovsky, 1980; Murphy, 1994; Bruce, 1995; Gringof et al, 2000 and other). Most of the approaches used may be formulated as follows.

Operational research methods are used to assess the efficiency of all economic decision variants and to choose the optimum strategy. A theory of optimum decisions was developed by Zhukovsky (1980). Operational research methods allow the user to "pre-assess the consequences of each decision, to reject the impermissible variants and to recommend the most suitable". Mean benefits (or mean losses) calculated with allowance for the probability of expected weather conditions using the Bayes-Lapcace principle are used as a criterion for choosing the optimum decision. Mean benefits are expressed by mathematical expectation in the following form:

$$\text{mean } \mathbf{U_j = \Sigma\, P_i\, U_{ij}}$$

where P_i is the probability of the i-th weather condition, $U_{i,j}$ are the benefits or losses of the j-th economic decisions under the i-th weather condition.

The optimum economic decision is chosen from the maximum weighted-mean benefits

$$U_{\mathbf{opt}} = \max\,(\text{mean } \mathbf{U_j})$$

The operation research apparatus may be a useful tool not only for choosing the optimum economic decisions, but also for assessing the economic efficiency of all possible decisions. This approach allows the development of specific methods of efficiency assessment for the above recommendations on agrometeorological applications to obtain the maximum production.

The aim of the above examples is to provide the final user of meteorological information its economic efficiency and to assess its efficiency in each specific situation. Only hydrometeorological information is meant here. Considering the sophistication of agricultural production and its sustainability, necessary decision-making requires a good deal of extra information and, thus, this problem may be solved only by developing the simulation model which includes agroclimatic, hydrometeorological, agrochemical, biological, economic, management and other parameters influencing decision-making in farming systems, forestry and livestock.

In this respect an important approach is a combination of dynamic models of plant development and economic models of different management factors (Thornton et al, 1994; Godwin et al, 1990; Johnson et al, 1991; Bogges and Ritchie, 1988; Alocilja and Ritchie, 1990).

1.4 METHODS AND TECHNOLOGIES OF AGROMETEOROLOGICAL APPLICATIONS

In recent years, CAgM has made every effort to study the impacts of climate, climate variability, and weather on agriculture.

As noted above (Baier et al, 1999), the problems to be solved by agricultural meteorology for sustainable agricultural production are outlined. The review (Sivakumar, 2000), presented at the Forty-Ninth Session of the WMO Executive Council "Climate variability and food production", deeply and comprehensively considers the application of knowledge about climate variability to raise food production under unstable environmental conditions. Some recent CAgM Reports discuss problems of agrometeorological applications for agricultural production, including sustainable development. Here we should mention CAgM Report No. 77b, (WMO 2001) that considers the main aspects of agrometeorological activities in the 21st century. CAgM Report No. 74 (Brunetti et al, 1997) discusses many problems of climate and weather impact on sustainable agricultural production. CAgM Report No. 87 (Pérarnaud et al, 2001) reviews the effect of agrometeorological conditions on the some crops production under changing climate conditions. CAgM Report No. 81 (Motha et al, 2000) discusses the present-day status of collection, accumulation, dissimilation and management of different agrometeorological data. Proceedings of the International Seminar "Climate Prediction and Agriculture", (Sivakumar ed 2000), alongside with general problems of agrometeorological and climatic forecasts, contain specific agrometeorological applications in different regions. Many aspects of agrometeorological information applications in different spheres of agricultural production and different world regions are considered in Proceedings of the International Seminar "User Requirements for Agrometeorological Services" (Sivakumar et al eds, 1998).

According to (Hrbek, 1983; Sivakumar, 2000; Motha, 1999), the meteorological community can help the agricultural community in developing strategies for coping with climatic variability by placing increased emphasis on three areas:

- strategic planning studies for the assessment of natural resources to enable long-term development planning or crop diversification;
- tactical approaches to monitoring short-term variations in crop growth and development due to intraseasonal variations in weather in order to facilitate operational decision-making during the growing season;
- operational decisions by improving long-term weather forecasting to help counter climate-induced variability and to help agriculture adaptation to changing conditions.

It should be emphasized here that there are no clear boundaries between the above areas. Strategic information may be used for tactical decisions and sometimes it is difficult to distinguish between tactical and operative ones.

Strategic planning is mainly concerned with the evaluation of natural resources in a regional and global scale and global climate change. Recently, numerous research has been performed under the aegis of WMO (Brunetti et al, 1997; Pérarnaud et al, 2001; Sivakumar eds, 2000). A great number of methods and techniques has been developed in order to calculate climate change and its impact on agriculture (Bruce, 1995; Rosenzweig et al, 1994; Sirotenko, 2001; Wilby and Wigley, 2000; Hansen and Jones, 2000; Parry, 1990; Salinger et al, 1980; Smith, 2000, Parton et al, 1987).

As an example, consider the change in four major (Parton et al, 1987) crops yield obtained under GCM scenario in CO_2 doubling (Sirotenko, 2001) (Table 1). Despite rather great scatter in calculation variations, a certain tendency in available materials is followed.

To present the above models in operation, let us describe the simulation Climate-Soil-Yield model developed in Russia (ARRIAM) (Sirotenko et al, 1997). The system includes:

- dynamical models of main crop yield formation;
- simulation model of energy and heat exchange in the soil-plant-atmosphere system;
- database on soils in the whole territory;
- complex of programmes for developing expanded climate change scenarios.

Table 1. Selected crop results for 2 x CO_2 equivalent equilibrium GCM scenarios

Region	Crop	Yield Impact (%)	Comments
Latin America	Maize	-61% to increase	Data are from Argentina, Brazil, Chile and Mexico; range is across GCM scenarios, with and without CO_2 effect
	Wheat	-50 to -5	Data are from Argentina, Uruguay and Brazil; range is across GCM scenarios, with and without CO_2 effect
	Soybean	-10 to +40	Data are from Brazil; range is across GCM scenarios, with CO_2 effect
Former Soviet Union	Wheat	-19 to +41	Range is across GCM scenarios and region, with CO_2 effect
	Grain	-14 to +13	
Europe	Maize	-30 to increase	Data are from France, Spain and northern Europe; with adaptation and CO_2 effect; assumes longer season, irrigation efficiency loss and northwards shift
	Wheat	Increase or decrease	Data are from France, UK and northern Europe; with adaptation and CO_2 effect; assumes longer season, northwards shift, increased pest damage and lower risk of crop failure
	Vegetables	Increase	Data are from UK and northern Europe; assumes pest damage, increased and lower risk of crop failure
North America	Maize	-55 to +62	Data are from USA and Canada; range is across GCM scenarios and sites, w/wo adaptation and w/wo CO_2 effect
	Wheat	-100 to +234	
	Soybean	-96 to +58	Data are from USA; less severe or increase with CO_2 and adaptation
Africa	Maize	-65 to +6	Data are from Egypt, Kenya, South Africa and Zimbabwe; range is over studies and climate scenarios, with CO_2 effect
	Millet	-79 to -63	Data are from Senegal; carrying capacity fell 11-38%
	Biomass	Decrease	Data are from South Africa; agrozone shifts
South Asia	Rice	-22 to +28	Data are from Bangladesh, India, Philippines, Thailand, Indonesia, Malaysia and Myanmar; range is over GCM scenarios, with CO_2 effect; some studies also consider adaptations
	Maize	-65 to -10	
	Wheat	-61 to +67	

China	**Rice**	**-78 to +28**	**Includes rainfed and irrigated rice; range is across sites and GCM scenarios; genetic variation provides scope for adaptation**
Other Asia and pacific Rim	**Rice**	**-45 to +30**	**Data are from Japan and South Korea; range is across GCM scenarios; generally positive in north Japan and negative in south**
	Pasture	**-1 to +35**	**Data are from Australia and New Zealand; regional variation**
	Wheat	**-41 to +65**	**Data are from Australia and Japan; wide variation, depending on cultivar**

Note: For most regions, studies have focused on one or two principal grains. These studies strongly demonstrate the variability in estimated yield impacts among countries, scenarios, methods of analysis and crops, making it difficult to generalize results across areas or for different climate scenarios.

The system allows the impact assessment of agricultural productivity of not only climatic parameters themselves, but also variations in greenhouse gas (CO_2 and surface O_3) content and soil fertility. Obtained data were included in the first and the second national Russian Federation reports on climate change.

Prompt dissemination of Roscomhydromet information on climate change in the decision-making allows preventive measures to be taken to reduce expenditures for overcoming the negative consequences of climate change. Besides, in the context of Russian Federation commitments within the United Nations Framework Convention on Climate Change (UNFCCC), the assessment of expected economic consequences of measures taken (first of all agricultural) in response to climate change is essential. Such assessments formed the basis of Russian agriculture development in 2000-2003 and beyond.

Calculation results with this system show that if the global surface temperature in Russia increases, a number of droughts will increase too, especially in southern Russian Federation regions, territories under forest will be re-distributed and desert-prone territories will appear. All this requires the corresponding concept of country development.

As an example, consider Table 2 (Sirotenko, 2001) which shows change in cereals and fodder crops under different scenarios for Russian Territory.

In strategic applications, agroecological zonation may play an important role. According to Sivakumar (2000), the food first focus of agricultural productivity research in the past occurring primarily on vertical relationships, i.e. investigations on plants, animals, air, water and soils within a relatively homogeneous spatial unit. However the present task of conserving and enhancing natural resources is more complex and carries an implicit recognition of the presence of several systems within a landscape, which calls for “horizontal analysis” requiring investigations and planning at temporal/spatial scales greater than the case with conventional studies. This requires integration of biological, physical and socio-economic factors in a holistic manner. The availability of tools such as geographical information systems (GIS) and other spatial modeling techniques make this possible.

The agroecological zonation approach presents a useful preliminary evaluation of the crop production potential (Sivakumar and Valentin, 1997) and ensures that representation is maintained at the appropriate biogeographic scale for regional sustainable development planning.

Let us characterize a similar agroecological zonation approach developed in Russia (Zhukov and Danielov, 1998; Zoidze and Shostak, 1996). This approach realizes an idea of successive decade-by-decade diagnostics observed during multiyear observations of weather conditions and assessment of its correspondence to crop requirements using image recognition algorithms and GIS elements. An approach allows to describe the behaviour of a system Climate-Yield with the help of the Markov chain apparatus and to give a probable forecast of different adverse weather situations and their impact on agriculture as a whole.

Table 2. The grain crop and fodder production response (changes in % of the present-day level) for entire Russia to possible changes in environmental conditions by the year 2030

Point	Possible changes in environmental conditions	Arid warming, GFDL		Humid warming, EMI	
		Crops		Crops	
		Grain	Fodder	Grain	Fodder
Changes of one factor					
1	Climate change	-15	-3	+9	+20
2	CO_2 increase	+15	+13	+15	+13
3	Ozone increase	-9	-6	-9	-6
4	Soil degradation	-13	-8	-13	-8
5	Optimized soil conditions	+119	+99	+119	+99
Changes of two factors					
6	Climate change and CO_2 increase	-2	+9	+26	+34
7	Climate change and soil degradation	-27	-14	-6	+6
8	Climate change and optimized soil condition	+74	+100	+146	+147
9	Soil degradation and CO_2 increase	0	+3	0	+3
10	Climate change and surface air layer ozone increase	-24	-11	-2	+11
Changes of three factors					
11	Climate change, ozone concentration increase and soil degradation	-35	-21	-17	-1
12	Climate change, CO_2 and ozone increase	-12	0	+11	+25
13	Climate change, CO_2 increase and soil degradation	-16	-1	+8	+20
Changes of four factors					
14	Climate change, CO_2 and ozone increase and soil degradation	-26	-9	-4	+11
15	Climate change, CO_2 and ozone increase, optimized soil condition	+67	+99	+136	+144

Note: Climate changes were calculated based on scenarios GFDL and EMI. The CO_2 increase means a 20% rise, the surface air ozone increase means a 30% rise. The soil degradation here means a 20% decrease in the humus budget.

In anomalous years the crop yield loss expressed in absolute values and its probabilistic assessments give important information for decision-making in agricultural production. This technology allows :

- to assess the observed weather day or decade situation as well as interphase or vegetation period as a whole relative to a particular crop or a crop complex within a regular network, administrative territory, region or farm;
- to give an agroclimatic forecast (by analogy) of most probable development of weather conditions in conformity to a particular crop and to assess its possible crop yield loss in case of unfavourable weather conditions;
- to estimate the natural-resource potential in conformity to principal crop growing areas within a regular network in the administrative area or region by calculating potential and climatically supported crop yield;
- to calculate the optimum sown area structure;
- to reduce the main hydrometeorological element fields with the account of their space variability and microclimatic corrections;
- to determine climatically appropriate areas of principal crop growing.

The CLICOM system serves the information basis for such technologies.

Jagtap (2001) gives an example of agroecological zonation for sub-Saharan Africa. The area of 340 km^2 or 18.5 by 18.5 km was used as a territory unit. Data on climate, soil, crops, socio-economic situation and some calculated agroclimatic characteristics such as vegetation period duration were inputted. The aim was to assess productivity and to develop recommendations on increasing agricultural production sustainability for some crops (rice, maize, sorghum, wheat, soy-bean).

Traditional agrometeorological applications, i.e. the use of crop yield and total harvest forecasts, on the basis of which management decision-making is executed, are very important for strategic planning of agricultural production (Kleschenko et al, 1996). There are different forecasting methods from common statistical ones to those using the present-day dynamic models Weather-Yield (Eurostat, 1994). As noted by Ford and Kanemasu (1997), modelling can be an important tool for testing and evaluating the sustainability of agricultural systems. Steiner (1987) identified the following uses and/or benefits associated with modeling:

- reductions in the need for site-specific, long-term field experiments;
- interpretation of climatological records in terms of production potential;
- evaluation of expected returns to management practices;
- evaluation of risks associated with management decisions;
- communications of research results between locations;
- enhanced understanding of biological, climatic, chemical and hydrological systems and their interactions
- conceptualization of multidisciplinary activities.

Despite the importance of model application in agrometeorology, sustainability problems were not considered in the first models (Parton et al, 1987; Johnson et al, 1991). However recent studies (Sirotenko, 2001, Polevoy, 2000) evidence that the application of fertilizers and pesticides for pest control in Weather-Yield models will allow to develop (recommend) the optimal (from the viewpoint of nutrition and contamination) fertilizer and pesticide applications taking into account weather conditions and forecast for the future or climatic information (Lablans and Mulder, 1997).

At present, satellite information is widely used for assessing crop conditions, crop productivity, and anomalous weather conditions (drought, frost etc) (Joint Research Council of the European Commission, 1994; Kleschenko et al, 1996, 1997; Kogan, 1995; Shili, 1996). Ford and Kanemasu (1997) state that one potentially important use for remote sensing is for the evaluation of genetic diversity in large plant collection. Remote sensing offers the opportunity to display and categorize plant attributes very quickly, thus allowing for a more effective use of the "core collections" that are used to develop crop varieties that exhibit desirable characteristics. The recent development of portable multispectral radiometers has made it possible to assess small plots and fields several times throughout the season. Ground level remote sensing offers the opportunity to display and categorize plant attributes of large field nurseries very quickly, yet avoids many of the classical problems (e.g. registration, atmospheric correction, pattern recognition, etc.) associated with large-scale remote sensing from satellite platforms. Traits that can potentially be measured using ground-level remote sensing include: seedling vigour, leaf area, light interception, canopy photosynthesis, growth duration, plant senescence, biomass production, plant height, plant lodging and heat and drought tolerance in terms of dehydration avoidance.

The strategic applications of agrometeorological knowledge discussed above are mainly concerned with long-term optimum crop distribution planning, development of recommendations on optimum conditions for crop growth and development and their productivity. However, within seasons, variations in weather elements have a profound influence on crop growth and yield. Currently, a wealth of meteorological information is available on a real time basis to users and the availability of high-speed computers should make it feasible to provide easy access to this information on a regional basis. This information could be used to give advice on operational decisions at the farm level to maintain crop yields. Such tactical decision-making is based on a sound knowledge of the effect of variations in weather elements and the current management practices at the field scale on growth, development and yield of crops. This requires an understanding of the physical and physiological processes governing crop growth. Tactical studies could address a variety of issues at different scales ranging from whole regions to individual fields. These applications, first of all, are stipulated by weather-responsive crop management tactics (Sivakumar, 2000). This paper gives concrete examples of crop system choice depending on the onset and the amount of rains that is very important for such regions as West African Sahel. Such tactics in some years allows inter-cropping depending on the soil moisture content that increases the productivity per area unit. Some weather and climate data applications to solve different problems at a farming level are also given (Sivakumar et al eds., 1998; Sivakumar ed. 2000). Gadgil et al (2000) cites the application of a decision-making system for nonirrigated zones with climate variability and the effects of precipitation variations that allows the development of decision support system considering different variants of field management. Types are determined for meteorological forecasts necessary for decision-making at different farming levels for nonirrigated ground-nut growing in Anantapur (India).

From a viewpoint of agricultural sustainability involving both the increase in productivity and the environmental control, we should consider a wide range of problems associated with forecasting pest and disease incidence. Pests, diseases, and weeds are the major biotic factors affecting crop production. Until recently, the major mode of control of pests and diseases was through the use of pesticides and fungicides. For example, the average consumption of pesticides in India has gone up from 3.2 g ha^{-1} in 1954-1955 to 15.4 g ha^{-1} in 1960-1961 to 640 g ha^{-1} in 1980 (Sivakumar, 2000). The amount of chemicals applied in the former USSR is stipulated by their production: 32.3 thousand tons were produced in 1960 and 280 thousand tons in 1980.

Such intensive application of chemicals has generated a problem of environmental control and contamination of agricultural products and the negative consequences of pesticides. Weather, climate and climate variability, which can be taken into account in modelling the impact of agrometeorological conditions on disease and pest development, contribute to the high efficiency of a chemical method of plant protection as well as to its ecological safety.

Quantitative operative evaluation and forecast of weather effects on the degree of disease and pest damage allows the replacement of preventive chemical treatments with the strictly necessary, maximum effective treatments (Volvach, 1987; Lablans and Mulder, 1997; Nwanze and Sivakumar, 1990). A direct consequence of agrometeorological applications for plant protection is smaller pesticide stress in crops due to the lower frequency and amount of chemical treatment.

Russian Roshydromet has developed the technique for automated forecasting of the Colorado beetle propagation intensity and volume corrections of potato chemical treatment. Decadal data on air temperature and precipitation sums from April to June, seasonal forecasts for the second half of summer, data on pest propagation intensity and preventive measures for the previous vegetation period are used for forecasting (Volvach, 1987). Testing this technique in Belorussia and 12 regions of Russian Federation demonstrated its high warrant and efficiency. Orientation of regional subdivisions of the State Service of Plant Protection to the forecasts obtained from the All-Russian Institute of Agricultural Meteorology and the Institute of Agrochemical Treatments allows to reduce the planned volumes of chemical treatments by 40-50%. In this case the efficiency of protection measures does not decrease.

A similar system for forecasting the terms of potato chemical protection from phytophthora was developed by the Institute of Plant Protection in co-operation with the All-Russian Institute of Agricultural Meteorology and the Central Designing Bureau. The system was based on prompt information about temperature, precipitation, relative air humidity as well as diurnal air temperature maxima and minima. Using actual data in a real time scale, the system evaluated the extent to which weather conditions were favourable for phytophthora and gave certain signals for the date of treatment. System application from expert assessments ensured the potato yield growth for about 1 mln roubles (1984 prices) (Lopatin, 1984).

Methodical and practical experience accumulated in the development of these two systems was expanded when working with autonomous measuring information-advicing complexes ELAGR (electronic agrometeorologist) for agrometeorological monitoring and phytosanitary forecasting (Volvach and Latushkin, 1996; Volvach and Utkiv, 1998). In classification, accepted by WMO for automated units, the complex ELAGR is to be referred to automated units operating as climatic stations, i.e. without output in communication channels in a real time regime.

The complex ELAGR realizes 10 applied forecast models of the development of the Colorado beetle, tetter, codling moth, leaf-rolling moth, fruit ticks, vine mildew and frost forecast. ELAGR was tested in the Moldavia, Tambov, Moscow and Kaluga regions. It was decided to install these complexes at regional plant protection sites. ELAGR-2 is a computer version of this system. ELAGR-2 software, a system of agroecological monitoring and phytosanitary forecasting, was developed for the Windows Operating System. According to the conclusion of All-Russian Selection-Technology Institute of Nursering and Gardening (Moscow), the introduction of ELAGR-2 for agrometeorological sustainability will result in a 15-25% fruit yield rise and a 30-40% drop of pesticide load on garden ecological systems.

Bouma and Wartena (1994) cited interesting examples how to combine agronomic and methodological knowledge for plant protection from chemicals and to choose pesticides and herbicides most suitable under different meteorological conditions. The effect of each reagent is evaluated from the impact of previous and observed weather conditions on plant tissues. Lablans and Mulder (1997) considered also the problem of soil and water contamination with agricultural chemicals. Significant air contamination can be caused by compost application.

Additionally, climate and weather variability influences both the occurrence and the dispersal of pests and pathogens. In India, the spread of stem rust of wheat uredospores is dependent on the November cyclones (Nagarajan and Singh, 1990). Nwanze and Sivakumar (1990) studied the relationships between rainfall, soil physical parameters, dispause and subsequent adult emergence during 1983-1986.

As already noted, tactical and operative approaches are difficult to be distinguished. Practically all examples of tactical applications may be considered as operative ones as they are based on applications of obtained agrometeorological recommendations to improve crop growth and development. Sivakumar (2000) points to applications of reliable long-range weather forecasting, seasonal forecasting in particular, as it could help farmers to take appropriate decisions as to which crops/cropping systems should be chosen well ahead of the sowing rains so that undue risks could be avoided. However long-range weather forecasting, especially forecasts of rainfall, is very difficult. Sivakumar (2000) gives several examples of seasonal rainfall forecasts for West Africa based on March and April sea-surface temperature anomaly patterns (Folland et al, 1991).

The most prominent, promising, and well-defined pattern of interannual variability is the global set of climatic anomalies referred to as El Nino/Southern Oscillation (ENSO) phenomenon. Sivakumar (2000) reviews the available models of El Nino forecasts and gives a practical example of this forecast application in Peru for choosing crop combinations which could be useful for the maximum crop yield in this region.

An important instrument in developing sustainable agriculture technologies is systems analysis (Ford and Kanemasu, 1997). Sustainable agricultural systems are complex and include agroecosystems, natural ecosystems, social systems and economic systems that are linked and interrelated in complex ways that are not easily quantifiable. Here hydrometeorological information should be an important component and is to be presented as an individual unit or included in natural ecosystems.

Ford and Kanemasu (1997) describe a system where climatic information is essential. This system was developed on the basis of the Sustainable Agriculture and Natural Resource Management – Collaborative Research Support Programme (SANREM-CRSP) using the modified farmer-back-to-farmer model (Rhoades et al, 1986) in which the user population is expanded to include not only farmers but also other individuals or grouped within a landscape. The landscape, as defined by the SANREM-CRSP, is a mosaic of interacting ecosystems. This approach is uniquely suited to the development of technologies for sustainable systems because it incorporates and address not only the interactions between ecosystems but also the primary interests and actions of end-users including individual farmers, farm households, rural and urban communities within the landscape.

Models are used (Ford and Kanemasu, 1997) in the SANREM-CRSP process:

1) at the field level to investigate the interactions between climatic and environmental conditions and farming systems, and to determine optimum crop and livestock management practices;
2) at the farm level to study the interaction between various farm enterprises;
3) at the household level to study issues related to economics;
4) at the community level to study traditional farming practices, indigenous knowledge, and the effect of farming system modification on the community economy and quality life;
5) at the watershed level to study the effects of current and modified farming practices on water quality;
6) at the ecosystem level to study the interaction of farming practices with the environment;
7) at the regional level to integrate the individual farm responses and to study regional production patterns;
8) at the national level to provide information on long-term policy effects of sustainable management systems.

So, system analysis is a powerful methodology that can be used to understand and develop appropriate technologies that help farmers and community achieve the multiple and dynamic goals of sustainability, including analysis and application of agrometeorological knowledge and knowledge of climatic variability.

1.5 GEOGRAPHIC INFORMATION SYSTEMS

Due to a growing load on land and water resources and a great variety of different effects, Geographic Information Systems (GIS) are uniquely suited for decision-making. The role of GIS in solving different agrometeorological problems, including sustainable agricultural production, was considered by many authors (Ford and Kanemasu, 1997; Motha, 1999; Maracchi et al, 2000, etc). A GIS is a computer-assisted system for acquisition, storage, analysis, and display of geographic data with hardware and software specially designed to cope with geographically referenced spatial data and corresponding informative attribute. GISs are uniquely suited for providing a framework in which data of multiple themes, but common geography, can be spatially displayed, analyzed and interpreted. An array of data and analytical options can be managed with GIS, including: spatial (e.g. land cover from remotely sensed imagery, topography from terrain models, transportation networks, soil and hydrology), attributes (e.g. crop yield, livestock populations, disease infestation, human population), that can be related to spatial entities, spatial interrelationships (e.g. covariance among soils, topography, hydrology and land cover) and simulation modelling (e.g. watershed response to changes in land cover). GIS are particularly appropriate for use in interdisciplinary and systems approaches to sustainable agriculture research because they provide a common framework for storage and analyses of both environmental and anthropogenic data and can be used to analyze the effects of integrated technology adoption.

The problem of the presentation of geographic elements is solved in two ways: using x,y coordinates (vectors) or representing the object as variation of values in a geometric array (raster). The possibility to transform the data from one format to the other allows fast interaction between different informative layers. Typical operations include overlaying different thematic maps, contributing areas and distances, acquiring statistical information about the attributes, changing the legend, scale and projection of maps, and making three-dimensional perspective view plots using elevation data.

The SANREM-CRSP model (Ford and Kanemasu, 1997) utilizes GIS as an integrative research tool in the development and evaluation of sustainable agriculture technologies. Specific uses of GIS in the SANREM-CRSP program include:

a) Registering and merging disparate multitheme data to a common base for multivariate analyses and modelling;
b) Providing effective data management and data awareness to link the multiple investigators;
c) Providing efficient data distribution in a ready useable form to the investigators and other who would benefit from the data;
d) Analyzing spatial relationships and map patterns of interrelated variables;
e) Conducting standard variance and covariance analyses and modelling to establish thematic and spatial linkages of the multiple data types;
f) Evaluating the impact of scale and detail of information on the resultant model for investigating locational dependencies and spatial extrapolation of the results to other watershed and to larger regions;
g) Facilitating effective visualization and communication of results to decision-making.

More than the classical applications, such as crop yield forecasting, uses such as those of the environmental and human security are becoming more and more important (Maracchi et al, 2000). For instance, effective forest fire prevention needs a series of information very detailed on an enormous scale. The analysis of data, such as the vegetation coverage with different levels of inflammability, the presence of urban agglomeration, the presence of roads and many other aspects, allows the mapping of the areas where risk is greater. The use of informative layers, such as the position of the control points and resource availability (staff, cars, helicopters, airplanes, fire fighting equipment and etc.), can help the decision-makers in the management of the territorial systems.

Monitoring the resources and the meteorological conditions therefore allows the consideration of system dynamics with more adherence to reality. The input data required are:

- Multitemporal satellite images (Landsat);
- Colour aerial photographs;
- High resolution digital elevation model of region;
- Vectorial map of roads;
- Vectorial map of municipality boundary;
- Informative technical schedule of the Tuscany Region for fire events (period 1984-1996);
- Direct measurements.

The final map is a result of integration of satellite data and territorial information using introduced GIS technologies (Romanelli et al, 1998). When introduced data are processed and analyzed, the maps of fire risk in different years are available.

Applications of GIS in agricultural meteorology are promising. Detailed data on meteorological parameters, plant vegetation, soil and water form complex informative levels. GIS allows users to obtain the final product in a form accessible. In agrometeorology, meteorological on-site and on-field data (phenological observations, agronomical indices, information about pest and disease propagation, soil characteristics etc.) serve the basis for different agrometeorological calculations and forecasts. These input data give a real model of the territory and may be used in the development and the application of models describing different interrelationships within this territory. Different types of agrometeorological models (from statistical to dynamic) may be introduced into GIS that allows the solution of a specific problem, i.e. current evaluation of crop growing conditions or crop yield forecasting for definite conditions of the territory under consideration (soil type, relief, microclimate etc).

In developing countries (where the informative layers are often unreliable and even lacking), GIS use can be promoted through the transfer of technologies and information from the developed ones (Maracchi et al, 2000). The general philosophy of the projects, finalized to produce GIS, is to realize more and more complex integrated systems and to satisfy the needs of users. In developing countries, the approach has to be quite different, initially realizing sufficiently simple systems, which answer specific problems, and then arriving gradually to complete the different informative layers and to create a fully operative GIS. An example of the 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 SISP uses:

- Statistical analysis procedures on historical series of rainfall data to produce agroclimatic classification;
- A crop (millet) simulation model to estimate millet sowing date and to evaluate the effect of the rainfall distribution on crop growth and yield;
- NOAA-NDVI image analysis procedures in order to monitor vegetation condition;
- Analysis procedures of Mutest images of estimated rainfall for early prediction of sowing date and risk areas.

The results of the SISP application shown for Niger are charts and maps, which give indications to the expert of the millet conditions during the season, with the possibility to estimate the moment of the harvest and final production. SISP is based on the simulation of the millet growth and it gives an index of annual productivity (range 0-1) by administrative units. These values, compared to the historical crop yields of the single administrative unit, allow the estimation of the expected productivity.

By means of similar systems like this, based on modelling and remote sensing, it is possible to extract indices relative to the main characteristics of the agricultural season and conditions of natural systems. This system is less expensive, easily transferable and requires minor informative layers, adapting it to the specific requirements of the users.

When the information available on the territory is sufficient, the passage of all this information to a GIS is immediate (Marrachi et al, 2000). An example in this regard is the environmental information system (EIS) realized by the PEICRE project for the department of Keita (Niger), starting from a large data set collected on this area (2.500 km^2). The data collected and the different information layers are organized in a database and all the information about the territory is integrated in a GIS. Each layer is composed of different archives (numerical data, text and images), which were preliminary controlled and evaluated. The archives are completed with graphical representations of the main data trends and synthetic information, obtained by means of spreadsheet and statistical software (Genesio and Di Vecchia, 1998).

The most important information is extracted to describe the territory and then combined for understanding the possible relationships between the different factors. The representation of these data can be made for discrete or continuous values, to obtain thematic maps or territorial representation of the spatially distributed parameters. The combination of all the information can give a synthetic representation of the reality.

An analysis of Landsat TM, MSS and SPOT multispectral images has been used to update the available maps and to obtain territorial classifications. The classification procedure is based on the integration of the different information layers (digital cartography, on-field observation, multispectral satellite images, aerial photographs etc.).

In the EIS-PEICRE system some models are also introduced, which are able to simulate the behaviour of different parameters or show possible scenarios. In particular, great importance is given to water and soil degradation. For instance, the evaluation of the erosion hazard requires many different layers for the application of the RUSLE model (Renard et al, 1994), derived from the USLE equation:

$$\mathbf{A = R\ K\ L\ S\ C\ P}$$

where A is the soil loss (t/ha/year); R represents rainfall and runoff erosivity; K is the soil erodibility; L represents slope length; S is the slope steepness; C represents cover management and P denotes supporting practices.

The erosivity (R factor) is calculated using rain data; the K values, given to each class of soil, are evaluated using all the available information and indications derived from ground observations. Cover management and supporting practices have been introduced by means of combinations of different information: digital cartography, on-field observation, aerial and satellite photographs. The heart of the model is a Digital Elevation Model (DEM) of the land, which allows the evaluation of the morphological factors (L and S of the USLE) for each point of the territory and the estimation of the water flow direction.

These new powerful tools give the possibility to introduce a new coefficient for the USLE, that was called the transport capacity factor (T) and represents the soil transport capacity of the water flow in each element (pixel). The simple multiplication of the resulting layers, each with its own series of values for each territorial unity, allows the evaluation of the erosion hazard in the considered time period.

In comparison between the erosion in 1984, before the intervention of land recovery, and 1995, after realization of the agronomic works by the environmental recovery and preservation project PIK (Integrated Project Keita), the positive effect of the agronomic works in the reduction of erosion has been evaluated. This effect is due to the increase of the vegetation coverage and to a better water management (Rapi et al, 1996). The GIS use in assessing the territory with the account of different soil characteristics and topography for sustainable agricultural production is given (Ahamed et al, 2000).

The examples presented here show the increasing role of GIS for solving different agrometeorological problems, including sustainable agricultural production.

1.6 ON POTENTIAL EFFECT ASSESSMENT

As to the economic efficiency of agrometeorological applications, it should be noted that these calculations are complex and in most cases we may speak only about potential effect.

The practices of hydrometeorological support suggest that data on dangerous meteorological phenomena and sudden weather changes have the highest economic effect. Besides, weather modification activities are also effective (Bedritsky, 1995). More than 30 years ago antihail operations were organized in Russia to protect crops from hail, now these activities are carried out in the territory of 1.8 mln ha. The experience available in antihail operations shows that their efficiency is about 75%. It means that hail damage in the protected territory is by 3-4 times lower as compared to that in this area before antihail operations.

A successful frost forecast in May 1994 in Omsk region allowed a later planting date of early vegetable crops and prevented damage amounting to 1.5 mln US dollars. Resowing winter crops in spring based on agrometeorological recommendations is also effective.

As the survey by questionnaire among the national meteorological/hydrological services (NHMS) on the economic efficiency of applications of climatological and meteorological data showed, the relative economic effect of these applications in various countries is 3-30 fold higher than the budgetary provisions for NHMSs. However in most cases the economic effect was determined without evaluating the ecological production safety, sustainable development etc. Therefore these calculations seem to be essential.

1.7 REFERENCES

Ahamed, T.R.N., K.G. Rao, and S.R. Murthy. 2000. GIS-based fuzzy membership model for crop-Land suitability analysis. Agricultural systems, Vol.63(2), pp.75-95.

Alocilja, E.C. and J.T. Ritchie 1990. The application of SIMOP T2: Rice to evaluate profit and yield-risk in upland-rice production. Agric. Syst. 33(4): 315-326.

Baier, W., R. Gommes, and M.V.K. Sivakumar. 1999. Agrometeorology and sustainable agriculture. WMO Bulletin. 48(4): 374-379.

Bedritsky, A.I. 1994. Economic benefits evaluation of hydrometeorological services in the Russian Federal Service for Hydrometeorology and Environmental Monitoring (ROSHYDROMET) taking into account changes in country's economy. Conference on the Economic Benefits of Meteorological and Hydrological Services, Geneva, Switzerland, WMO/TD. No.630. p.121-125.

Boggess, W.G., and J.T. Ritchie. 1988. Economic and risk analysis of irrigation decisions in humid regions. J.Prod.Agric.I (2): 116-122.

Bouma, E., and L. Wartena. 1994. The influence of weather on pesticides. PAGV Report N 166. (In Deutch)

Brown, L.R., C. Flavin, And H. Hame. 1996. Vital signs 1996-97. The trends that are shaping our future. Earthscan Publications, Ltd.,London.

Bruce, J.R. 1995. Economic substantiation of climate change studies – potential value of climatic information for final users. In: New tendencies in hydrometeorology. Vyp.2.Theses. Moscow.

Brunetti, A., P.B. Ford, E.T. Kanemasu, W.N. Lablans, P.F. Mills, R. Mulder, O.D. Sirotenko, and F. Wang. 1997. Weather/Climate and Sustainable Agricultural Production and Protection. CAgM Report No. 74. WMO/TD-No. 838. 112 pp.

Di Chiara, C. and G. Maracchi. 1994. Guide on S.I.S.P. ver.1.0. Technical Manual No.14, GSIA, Firenze, Italy.

Eurostat, 1994. Crop Yield Forecasting Methods. Proceedings of the Seminar, Villefranche-sur-Mer, 24-27 Oct. 1994., Eurostat, JRP-Ispra, DG VI and FAO. ECSC-EC-EAEC, Luxembourg.

Fedoseev, A.P. 1979. Agrotechnics and weather. – L.,Hydrometeoizdat, 240 pp.

Folland, C.K. et al, 1991. Journal of Forecasting, 10, p.21-56.

Ford, F.B. and E.T. Kanematsu. 1997. Methods to transform basic knowledge into operational techniques for use elsewhere. Weather/Climate and Sustainable Agricultural Production and Protection. CAgM Report No. 74. WMO/TD-No. 838. p 67-90.

Gadgil, S., R.R.S. Rao, and K.N. Rao. 2000. Farming strategies for a variable climate. Pages 215-248 *In:* Climate Prediction and Agriculture. Proceedings of the START/WMO International Workshop held in Geneva, Switzerland, 27-29 September (M.V.K. Sivakumar ed.) Washington, D.C. U.S.A. International START Secretrariat.

Gatzweiler, T. Sipilainen, S. Backman, and A. Zeller. 2001. Analyzing institutions, policies and farming systems for sustainable agriculture in central and eastern European countries. CEESA Discussion Paper No.215, 52 pp.

Genesio, L. and Di Veechia, A., 1998. Le Systeme d'Information Environmental SIE-P.E.I.C.R.E., Technical Report, PEICRE PROJECT, CESIA, Firenze, Italy.

Godwin, D.C., P.K. Thornton, J.W. Jones, V. Singh, S.S. Jagtap, and J.T. Ritchie. 1990. Using IBSNATs DSSAT in strategy evaluation. p.59-71. In: Proc.Int.Benchmark sites network for agrometeorology. Transfer Project Symp.: Decision on support system for agrometeorology transfer. Dep. Of Agronomy and Human Resources, Univ.of Hawaii, Honolulu.

Gringof, I.G., A.D. Kleschenko, and O.K. Ustinova. 2001. Achievements and problems of developing procedures for economic efficiency assessment of agrometeorological support of agrarian sector of Russian economy.Proceedings of ARRIHMI-WDC,vyp.168, Hydrometeoizdat.

Hansen, J.W., and W.J. Jones. 2000. Scaling-up crop models for climate prediction applications. Pages 77-117 *In:* Climate Prediction and Agriculture. Proceedings of the START/WMO International Workshop held in Geneva, Switzerland, 27-29 September (M.V.K. Sivakumar ed.) Washington, D.C. U.S.A. International START Secretrariat.

Hrbek, J.,1983. Meteorological forecasts and other services for agriculture. Eppo Bull. 13, p.915.

Jagtap, S.S. 2001. Planning sustainable agriculture using agroclimatic databases. Agrometeorological Information Needs in Agricultural Production. CAgM Report No.85. WMO/TD No.1030. Geneva, Switzerland. p. 65-85.

Joint Research Council (JRC) of the European Commission. 1994. The MARS project: overview and perspectives. ECSC-EC-EAES, Brussels, Luxemburg, 166 pp.

Johnson, S.L., R.A. Adams, and G.M. Pery. 1991. The on-farm costs of reducing groundwater pollution. Am.J.Agric.Econ. 73,p.1063-1073.

Kleschenko, A.D., V.M. Pasov, A.I. Strashnaya. 1996. Present-day status and prospects of developing agrometeorological forecasts. Theses of scientific conference reports on studies in hydrometeorology and environmental contamination monitoring. Moscow, Section 1.

Kleschenko, A.D. and O.V. Virchenko. 1996. Applications of remote sensing data to operational agrometeorological practice. Proceedings of the 1995 Meteorological Satellite Data Users' Conference, Eumetsat, p.217-222.

Kleschenko, A.D., and O.D. Sirotenko, and O.V. Virchenko. 1997. Applications of Weather-Soil-Yield models and remote sensing data to crops state and productivity monitoring in Russia. Proceedings of the seminar Crop Yield Forecasting Methods, Eurostat, Luzembourg, 1997, p.425-432.

Kogan, F. 1996. A VHRR data for detection and analysis of vegetation stress. Proceedings of the 1995 Meteorological Satellite Data Users'Conference, Eumetsat, p.155-162.

Lablans, W.N. and R. Mulder. 1997. Problems relating to high industrialization and agriculture, including aspects of quality of produce and degradation of the environment. Weather/Climate and Sustainable Agricultural Production and Protection. CAgM Report No.74. WMO/TD No.838. p. 103-112.

Lampe, K.J. 1996. Rural misery and agricultural decline in resource-poor, fast growing Countries. The Globalization of Science: The Place of Agricultural Research (C.Bonte-Friedheimand K.Sheridan, eds.), International Service for National Agricultural Research, The Hague,p.61-72.

Lopatin, V.P. et al. 1984. Experimental automated users'information system on environmental Conditions. M. Hydrometeoizdat, 72 pp.

Maracchi, G., V. Perarnaud, and A.D. Kleschenko. 2000. Applications of geographical information systems and remote sensing in agrometeorology. Agricultural and Forest Meteorology, 103, 119-136.

Maunder, W.J. 1989. Climatic variability and agricultural production in temperate regions: six case studies. Climate and Food Security, International Rice Research Institute, Manila, p.45-55.

Mills, P.F. 1997. Agrometeorological aspects and application of available technologies to help promote the development of sustainable farming systems. Weather/Climate and

Sustainable Agricultural Production and Protection. CAgM Report No.74 WMO/TD No.838. p. 1-28.

Moiseev, N.N. 1994. The biota as a regulator and the sustainability problem. Comp.Math. Phys., 34 (4), p.453-462.

Motha, R.P. 1999. Management of agrometeorological data, WMO Bull. Vol.48, No.4, p.443-450.

Motha, R.P., Bernard, M., H. Hayhoe, D. Kleschenko, B. L. Lee, L. Leskinen, and O. Virchenko. 2000. Agrometeorological Data Management. CAgM Report No. 81. WMO/TD No. 1015. 98 pp.

Murphy, A.H. 1994. Assessing the economic value of weather forecasts: an overview of methods, results and issues. Meteorological Applications, 1, p.69-73.

Nagarajan, S. And D.V. Singh. 1990. Long-distance dispersion of rust pathogens. Annual Review of Plant Phytopathology, 28, p.139-153.

Nwanze, K.F. and M.V.K. Sivakumar. 1990. Insect pests of pearl millet in Sahelian West Africa-II. Raghuva albipunctella de Joannis (Noctuidae, Lepidoptera).

Parry, M.,1990. Climate change and world agriculture. Earthscan Publications Ltd.L., UNEP, NASA, 1990, 157 pp.

Parton, W.J. et al, 1987. Analysis of factors controlling soil organic matter levels in Great Plains Grassland, Soil Sci., Soc.Am.J.,Vol.51, p.1173-1179.

Pérarnaud, V., A.K. Chan, M.A.A. Dawod, S.K. Shaha and O. Sirotenko. 2001. Report of the CAgM Working Group on Weather and Climate related to Agricultural Production. CAgM Report No. 87. WMO/TD No. 1079. 113 pp.

Polevoy, A.N. 2000. Modelling anthropogenic agroecosystem contamination under extreme conditions. Proceedings of ARRIAM. Vyp.33. p.134-149.

Rapi, B., C. Conese, and G. Maracchi. 1996. Risque d'erosionet evaluation des œuvres hydraulico-agraires du PIK. PEICRE, RT2, CeSIA, Firenze, Italy.

Renard, K.G., J.M. Laflen, G.R. Foster, and D.K. Mc Cool. 1994. The revised universal soil loss equation. In: Lal,R. (Ed.), Soil Erosion Research Methods. The Soil and Water Conservation Society and St.Lucie Press. USA.

Rhoades, R.E., M.J. Potts, R.H. Booth, D.E. Horton, and M. Upadhya. 1986. Generating Appropriate technologies with small farmers: The CIP Approach. In: International Agricultural Research Centres Proceedings of the Workshop on Farming Systems Research. 17-21 February 1986, ICRI SAT Center, India.

Romanelli, S., L. Bottai, F. Maselli. 1998. Studio preliminare per la stima del rischio d'incendio boschivo a scala regionale per mezzo dei dati satellitari e ausiliari. Tuscany Region – Laboratory for Meteorology and Environmental Modelling (LaMMA), Firenze, Italy.

Rosenzweig, C., et al, 1994. The effects of potential climate change on simulated grain crops in the United States. C.Rosenzweig and A.Iglesias (Eds.). Implications of Climate Change for International Agriculture: Crop Modelling Study.EPA 230-B-94-003.

Salinger, M.J. et al, 1980. CO_2 and climate change: impacts on agriculture, New Zealand Met.Service, Willington, New Zealand, 29 pp.

Shili, W. 1966. Remote sensing applications to agrometeorology in Asia. Chinese Academy of Meteorological Sciences. The Review submitted to WMO, 37 pp.

Sirotenko, O.D., E. Abashina, And V. Pavlova. 1997. Sensitivity of the Russian agriculture to changes in climate, CO_2 and tropospheric ozone concentrations and soil fertility. Climatic change, 36, p.217-232.

Sirotenko, O.D. 2001. Review and summary of methods used for the assessment of possible adaptation by farming systems and by the agricultural sector to climate change and climate variability. Report of the CAgM Working Group on Weather and Climate related to Agricultural Production. CAgM Report No.97. WMO/TD No.1079. p. 81-111.

Sivakumar, M.V.K. and C. Valentin. 1997. Agricultural zones and the assessment of crop production potential. Philosophical Transactions of the Royal Society of London.B.

Sivakumar, M.V.K., U.S. De, K.C. Sinta Ray, and M. Rajeevan Ed (eds). 1998. User requirements for Agrometeorological Services. Proceedings of an International Workshop held in Pune, India, 10-14 November 1997. Pune, India. India Meteorological Department and WMO. pp. 336.

Sivakumar, M.V.K. 2000. Climate variability and food production. Lectures Presented at the Forty.Ninth Session of the WMO Executive Council. WMO. No. 910. Geneva, Switzerland. p. 1-18.

Sivakumar, M.V.K., R. Gommes, and W. Baier. 2000. Agrometeorology and sustainable agriculture. Agricultural and Forest Meteorology, 103(1-2), p.11-26.

Sivakumar, M.V.K. (Ed.). 2000. Climate Prediction and Agriculture. Proceedings of the START/WMO International Workshop held in Geneva, Switzerland, 27-29 September 1999. Washington D.C., USA, International START Secretariat.

Sivakumar, M.V.K., C.J. Stitger, and D.A. Rijks. (Eds.), 2000. Agrometeorology in the 21st century – needs and perspectives. Special Issue on the Proceedings of the WMO/CAgM organized International Workshop in Accra, Ghana, 15-17 February 1999. Agricultural and Forest Meteorology, 103(1-2).

Smith, M. 2000. The application of climatic data for planning and management of sustainable rainfall and irrigated crop production. Agricultural and Forest Meteorology, Vol.103 (1-2), p.99-108.

Steiner, J.L. 1987. Modelling agroclimatic systems: Guidelines and perspectives. In: Renar C., Van Den Belt, R.J. and Parr, L.F.(Eds.), p.341-351. Soil crop and water management systems for rainfed agriculture in Sudano-Sahelian zone. Proceedings of an International Workshop. 11-16 January, Niamey, Niger.

Stigter, K. 1999. Future of agrometeorology: perspectives of science and practice. WMO Bulletin 48(4) October 1999, p.435-443.

Swaminathan, M.S. 1996. Uncommon opportunities for achieving sustainable food and nutrition security. An agenda for science and public policy. The globalization of science. The place of agricultural research (C.Bonte-Friedheim and K.Sheridan, (Eds.). International Service for National Agricultural Research. The Hague, 2001, p.119-126.

Tarko, A.M. 1995. Sustainability of biospheric processes and Le-Chatelie's principle AN Reports, Vol.343, No.3, p.393-395.

Thorton, P.K. and G. Hoogenboom. 1994. A computer program to analyze single-season crop model outputs. Agronomy Journal, Vol.86, No.5

United Nations Conference on Environment and Development (UNCED). 1992. Earth summit Agenda 21, the United Nations programme of action from Rio: Final text of agreements negotiated by Governments at the United Nations conference on Environment and Development (UNCED); 1992 June 3-14; Rio de Janeiro, Brazil. United Nations. Publication Sales No. E.93.I.11.

Volvach, V.V., 1987. Modelling impact of agrometeorological conditions on the Colorado beetle development. L.Hydrometeoizdat, 240 pp.

Volvach, V.V. and V.N. Latushkin. 1996. Complex automated monitoring in gardening. Achievements in science and technology.APK., 1996, No.3, p.26-28.

Volvach, V.V., and Yu A. Utkiv. 1998. Experience of development and fixation of automated complexes for agrometeorological monitoring and photosanitary forecasting in gardening. Theses of the All-Russian Meeting, M.,p.89-91.

Wilby, R.I. and T.M.L. Wigley. 2000. Downscaling general circulation issues in climate prediction Pages 39-69 *In:* Climate Prediction and Agriculture. Proceedings of the START/WMO International Workshop held in Geneva, Switzerland, 27-29 September (M.V.K. Sivakumar ed.) Washington, D.C. U.S.A. International START Secretrariat.

Wiren-Lehr, S. 2001. Sustainability in agriculture: an evaluation of principal goal-oriented concepts to close the gap beteen theory and practice. Agriculture, ecosystems and environment, vol.84(2), pp.115-129.

WMO, 2001. Contributions from Members on Operational Applications in Agrometeorology in the International Workshop: “Agrometeorology in the 21st Century, Needs and Perspectives”. CAgM Report No. 77b., WMO/TD 1029. 173 pp.

Zellei, A. 2001. Challenges for agri-environmental policies in CE countries. CEESA Discussion paper No.3/6, 33 pp.

Zhuchenko, A.A. 2001. Adaptive system of plant selection (Ecologic-genetic fundamentals). Monography. Moscow, Publishing House Agrorus Ltd.

Zhukov, V.A. and S. A. Danielov. 1998. Agricultural specialization with allowance for agroclimatic resources of Russia. Meteorology and Hydrology, No.6, p.92-99.

Zhukovsky, E.E. 1980. Meteorological information and economic decisions. L.,Hydrometeoizdat, 303 pp.

Zoidze, I.K. and Z.A. Shostak. 1996. Assessment of using agroclimatic resources in Russia. Meteorology and Hydrology, No.10.

CHAPTER 2

IMPACT OF AGROMETEOROLOGICAL APPLICATIONS FOR SUSTAINABLE MANAGEMENT OF FORESTRY

by Robert Stefanski
World Agricultural Outlook Board
United States Department of Agriculture
E-mail: RSTEFANSKI@mailoce.oce.usda.gov

2.1 INTRODUCTION

The Working Group on Impacts of Agrometerological Applications for Sustainable Management of Farming Systems, Forestry, and Livestock was established during the 12th session of the World Meteorological Organization's (WMO) Commission on Agricultural Meteorology (CAgM) held in Accra, Ghana in February 1999. This group was charged with compiling, reviewing and summarizing the impacts of proven, effective agrometeorological applications for the sustainable management of farming systems, forestry, and livestock. In meeting this goal, the group members have stressed that the agrometeorogical applications should propagate sustainability and that concrete examples of these applications should be provided from both the developed and developing countries. Members were particularly concerned that the applications take into account the lack of adequate economic resources and trained personnel in developing countries, for these factors limit the countries' choices to simple, well tested, low-cost systems.

Why should an emphasis be placed on sustainable management? As discussed by Baier, Gommes, and Sivakumar (1998), sustainable management is needed because of rising population growth, diminishing arable land (especially in developing countries) and declines in non-renewable energy and environmental degradation. Because of these concerns, the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro, Brazil, during June 1992, proposed activities for the CAgM to explore. The UNCED's Statement of Principles on Forests calls upon the CAgM to provide information on proper resource management and to develop a network for exchange of information. It also calls for research to be conducted on the following: the use of agrometeorological information for efficient, rational, and sustainable development; the use of forests and forest-based resources; and forestry activities that are non-degrading and have a value-added component such as wildlife conservation. It is the goal of this paper to address these issues by compiling, reviewing, and summarizing some of the agrometeorological applications related to forestry.

In the wide-ranging forestry field, there are several areas in which agrometerological applications can be used, including: fire behavior/danger, fire management, prescribed burning and fire effects, climate change, smoke management and air quality, and forest health and productivity. Fire is one tool that forestry managers use for the sustainable management of forest resources. One of the main concerns in forestry is fire's potential, behavior, management, and output.

Fox et al (2000) state that forest fires are a natural component of the forest ecosystems. Many forests require the regular presence of fire to maintain healthy, diverse, and productive ecosystems; the unnatural suppression of wildfire in the U.S. has produced ecosystems with reduced biological diversity, increased susceptibility by insects and diseases, and the potential for catastrophic fires. Furthermore, due to the negative impacts of wildfire on human economic values, wildfire cannot be tolerated. Therefore, a conflict exists between the ecological and practical benefits of fire to forests and the negative impacts of fire on human activities (i.e. loss of property, smoke). To illustrate the similar management issues in wildlands across the world, controlled burning is used to rejuvenate the vegetation and reduce fuel loads in the shrublands of southwestern South Africa (Juhnke and Fuggle 1987). Additionally, Van Wilgen et al (1984) states that these shrublands are managed for high streamflow, nature conservation, fire hazard reduction, afforestation, grazing, tourism, and recreation. In their chapter on "Global Fire", Pyne et al (1996) details similar conflicts and issues in several other countries around the world. All of these issues are related to the sustainable management of forests.

Weather plays a significant role in the fire environment (Pyne et al 1996). Federal fire managers in the United States recommend that fire danger rating indices, based in part on weather data, be considered part of a comprehensive set of criteria used to decide whether to control naturally occurring forest fires or to let them burn as part of a management strategy for reducing fuel load and/or ecological purposes (Andrews and Bradshaw 1995).

The many agrometeorological applications discussed in this paper were developed to help fire managers resolve the conflict between maintaining healthy forests and eliminating or reducing the impact on human activities.

It would be impossible to list in detail the inputs, methods, equations, and hardware needed for each relevant application. Since the working group expressed a need for simple, well tested, low-cost applications, these applications will be highlighted first within each section. However, since many countries have various levels of resources available, other more sophisticated applications will also be discussed. The references listed in this paper can be used as a starting point for further inquiry.

2.2 FIRE DANGER RATINGS

According to Pyne et al (1996), a fire danger rating is an index of fire potential for a large area. It is a method of integrating and interpreting seasonal weather as an indicator for fire potential. Fire danger rating systems are used as fire management guides such as staffing for fire control, scheduling prescribed fire, and fire prevention. Also, fire danger ratings are used to aid in presuppression fire activities, such as aircraft detection flights and prepositioning of fire fighters (Haines et al 1983). They are also used to track the fire season and allow the comparison of one season to another. Fire danger ratings do not predict how a specific fire will behave but measure the potential of fire occurrence. Several fire danger rating systems will be discussed including applications from Russia, Australia, the United States, and Canada.

Some fire danger ratings system combine fire danger and fire behavior. For the Australian system, this combination is discussed together in this section, while the Canadian system, the two are divided between the two sections.

Nesterov Index (Russia)

The most widely used fire danger rating system in Russia is a relatively simple ignition index called the Nesterov Index (NI). It provides a general index of ignition potential (Fosberg et al 1996; Stocks et al 1996). The daily weather requirements for this index are:

- Dry-Bulb Temperature
- Dew-Point Temperature (calculated from relative humidity and temperature)
- Precipitation.

The index is initialized at zero and is determined by taking the difference between the daily air (dry bulb) and dew point temperatures, multiplying this difference by the air temperature and then cumulatively summing up the values over the number of days since 3mm of precipitation has fallen. Once 3 mm or more of daily precipitation has fallen the index returns to zero (Buchholz and Weidemann 2000). The index is expressed mathematical (from Buchholz and Weidemann 2000) by

$$NI = \sum_{i=1}^{W} (T_i - D_i) * T_i$$

where

NI = Nesterov Index
W = number of days since 3mm of rainfall
T = Temperature (^oC)
D = Dewpoint temperature (^oC)

According to Fosberg et al (1996) the index scale is :

- Less than 300 – Low Ignition Potential
- 300 to 1000 – Moderate Ignition Potential
- 1000 to 4000 - High Ignition Potential
- Greater than 4000 – Extreme Ignition Potential

According to Pyne et al (1996), the NI is used to schedule daily fire operations in the Russian Federation. From Stocks and Lynham (1996), the NI has been calibrated by various Russian researchers for regional conditions and a logarithmic version of the index was produced to decrease the disparity between the regional scales (see suggested other readings).

Keetch-Byram Drought Index (U.S.)

Keetch and Byram (1968) developed a drought index specifically to be used assess fire potential. It is a continous index representing the net effect of evapotranspiration and precipitation in cumulative moisture deficiency in deep duff and upper soil layers, as well as the flammability of organic matter. Duff is the humus layer on the forest floor consisting of decomposing litter (needles, leaves, and other dead vegetation) and mineral soil (Pyne et al 1996). The Keetch-Byram Drought Index (KBDI) estimates the amount of precipitation necessary to return the soil to full field capacity. It is scaled from 0 to 800 units to represent 0 to 8 inches of soil moisture. At zero, the KBDI assumes saturation at 8 inches of water and therefore no moisture deficiency. At 800, the KBDI indicates the maximum drought possible. Between 0 and 800, the index represents the amount of net rainfall in hundredths of inches required to reduce the index to zero (Pyne et al 1996). The inputs of the KBDI are:

- Previous day's KBDI
- Long-term mean annual precipitation (inches; preferably 30-year average)
- Maximum or time of observation dry bulb temperature (^oF)
- Daily (24 hour) precipitation (inches)

The following description comes from Keetch and Byram (1968). The KBDI is calculated by using a simple daily bookkeeping procedure, composed of two steps: reducing the previous day's index by the net rainfall and then increasing the index by a drought factor.

First, the net rainfall is determined by subtracting 0.20 from the daily rainfall; if the rainfall is less than 0.20 inches, then the net rainfall is zero. If there are consecutive days of precipitation with no drying of the tree canopy between showers, subtract 0.20 only once on the day that the cumulative rainfall exceeds 0.20 inches. Afterwards, consider all daily rainfall net rainfall until there is a day without rain.

Next, multiply the net rainfall by 100 to make the index a whole number. Subtract the net rainfall from the previous day's KBDI. This interim value is used to calculate the drought factor. The drought factor (representing evapotranspiration) is added to the interim value to obtain the current day's KBDI. The process can be depicted as:

$$Q = \text{Previous KBDI} - \text{Net Rainfall}$$

$$KBDI = Q + \text{Drought Factor (based on Q)}.$$

The drought factor can be determined by tables based on the annual rainfall (Keetch and Byram 1968) or the drought factor equation.

The original equation from Keetch and Byram (1968) contained some discrepancies in the constants that are corrected in the versions below. The following English unit and metric unit versions of the equations are from Alexander (1990). The English unit version of drought factor is:

$$DF = \frac{(800 - Q)\,(0.968 \exp(0.0486T) - 8.30)}{1 + 10.88 \exp(-0.0441R)} * 0.001$$

where

Q = the previous day's KBDI – Net Rainfall (hundredths of inches)
T = Maximum, or time of observation, dry bulb temperature (^{o}F)
R = Mean Annual Precipitation (inches).

The same procedure is followed for the metric version of the KBDI, except that the net rainfall is not adjusted by 100. The metric units are millimeters and degrees ^{o}C. The metric unit version of the drought factor is:

$$DF = \frac{(203.2 - Q)\,(0.968 \exp(0.0875T + 1.5552) - 8.30)}{1 + 10.88 \exp(-0.001736R)} * 0.001$$

Since the KBDI is a cumulative index, it relies on the previous day's index. This means that the KBDI must be initialized and therefore cannot always start at zero. The zero point implies saturation, so care must be taken when initializing the KBDI. Keetch and Byram (1968) recommend that when starting the index, one should go back to a period of abundant rainfall of 6 to 8 inches (150 to 200 mm) and set the index to zero.

Fujioka (1991) suggests that while selecting an invalid starting point will propagate errors, the errors will disappear after several years of calculating the index, especially if there is a wet period when the index reaches zero. There are various KBDI scales in use that reflect the local application and use. In general, the values indicate the following (WFAS, 2000):

- KBDI = 0 - 200: Soil moisture and large class fuel moistures are high and do not contribute much to fire intensity. Typical of spring dormant season following winter precipitation.

- KBDI = 200 - 400: Typical of late spring, early growing season. Lower litter and duff layers are drying and beginning to contribute to fire intensity.

- KBDI = 400 - 600: Typical of late summer, early fall. Lower litter and duff layers actively contribute to fire intensity and will burn actively.

- KBDI = 600 - 800: Often associated with more severe drought with increased wildfire occurrence. Intense, deep burning fires with significant downwind spotting can be expected. Live fuels can also be expected to burn actively at these levels.

A good online resource for more information about the background, initialization, calculations of the KBDI can be found at http://www.seawfo.noaa.gov/fire/olm/ KEETCH.htm.

Uses of the KBDI

The KBDI was incorporated into the United States National Fire-Danger Rating System (NFDRS) in 1988 to modify the amount of dead fuel available for consumption (Burgan 1988). A modified KBDI has been used for a Fire Danger Rating System in East Kalimantan on the island of Boreno in Indonesia for five years on an operational basis (Buchholz and Weidemann 2000) and for fire management in Sabah, Malaysia (Solibun and Lagan 1998). The KBDI is also used in the calculations of the Australian McArthur Fire danger meters for grasslands and forests.

Mcarthur Fire Danger Meters (Australia)

In Australia, McArthur (1966, 1967) developed a widely used fire danger and behavior index. It is based on over 800 experimental fires in a wide variety of fuel types, including eucalypt. The index is calculated by using fire danger meters for forests and grasslands. The Commonwealth Scientific and Industrial Research Organization (CSIRO) has updated these meters into the following: Grassland Fire Danger Meter (modified McArthur); Grassland Fire Spread Meter; Fire Spread Meter for Northern Australia; and Forest Fire Danger Meter (CSIRO 2000). These meters have been programmed into computer programs complete with help files and are compatible with Windows 95 & 98, Windows NT, and Windows 2000 (CSIRO 2000).

CSIRO based the forest fire danger index (FFDI) equations from Noble et al (1980). It should be pointed out that the equations used in the McArthur meters are not based on the original data, but represent a reasonable fit to the meters since many of the original data was not available (Noble et al 1980).

The forest fire danger index is based on the following equations from (Noble et al 1980):

$$D = 0.191 * (I + 104) * (N + 1)^{1.5} / (3.52 * (N + 1)^{1.5} + P - 1)$$

$$FFDI = 2.0 * \exp(-0.450 + 0.987 * \ln(D) - 0.0345 * H + 0.0338 * T + 0.0234 * V)$$

Where,

H = relative humidity (percent)
T = air temperature (degrees C)
V = average wind velocity at 10 m (km/hour)
P = Amount of precipitation (mm)
D = Drought factor
I = Keetch-Byram Drought Index (mm equivalents)
N = Number days since rain

From McArthur (1968), the FFDI is based on a scale from 0-100, where a rating of 1 represents a fire that will not burn, or that will burn so slowly that control is very easy, and 100 represents a fire that will burn so fast and so hot that control is virtually impossible. The meter also can be used to determine the rate of forward spread of fire on level and sloping ground, flame height, and the distance of spotting from flame front (Noble et al 1980). The advantage of these meters is that they can be used by fire managers in the field using real-time or hourly weather data.

Gill et al (1987) examined the use of two drought indices in the calculation of FFDI for Melbourne, Victoria. They found that statistically, there was little difference in the FFDI whether the Keetch-Byram Drought Index (KBDI) or the Mount soil dryness index (SDI) was used. However, by using the SDI, the number of extreme days was 50% greater than the KBDI. They found that the number of forest fires in Victoria was fairly well correlated with the 3 p.m. FFDI at Melbourne.

The current Grassland Fire Danger Meter uses some of the same relationships as McArthur's, but omits the rate of spread and makes it into a separate CSIRO Grassland Fire Spread Meter. Also, the index value is open-ended and can exceed 100 (CSIRO 2000). The Grassland Fire Danger Meter uses only one fuel variable (the percent of curing) and is then combined with temperature, relative humidity, and wind speed. This creates an index of the degree of difficulty of suppressing fire in a standard average pasture (Figure 1). There are five fire danger rating classes: low, moderate, high, very high, and extreme (CSIRO 2000).

The Grassland Fire Spread meter was developed because it was found that the conditions that affect relative fire danger are not applicable to fire spread in the same way (Cheney and Sullivan 1997). This meter predicts a fire's potential rate of forward spread over periods of 15-20 minutes across continuous grassland. The slope of the ground is not included (CSIRO 2000; Cheney and Sullivan 1997).

The Fire Spread Meter for Northern Australia was designed to predict the rate of spread of fires in open grassland, woodland, and open forest with a grass understory. It is not suitable for predicting fire spread in tall, closed forest or a tall forest with substantial shrub and litter. However, it is suitable to predict fire spread for grass fuels that are largely undisturbed or only grazed lightly (CSIRO 2000).

Hall and Gwalema (1985) derived a drought index and fire danger rating for Tanzania based on the methods of McArthur Fire Danger Meter. By using 12-years of data and the drought index, they concluded that controlled burning is feasible in Tanzania after the rainy season.

The United States National Fire-Danger Rating System (NFDRS) has been used by the United States Forest Service for the past thirty years (Figure 2). The current system was developed in 1972 (Deeming et al 1972) and revised in 1978 to include a better response to short-term drought, increased seasonal sensitivity, additional fuel models and other modifications (Bradshaw et al 1984). The NFDRS was further revised in 1988 with the addition of Keetch-Byram Drought Index to account for weather and climatic conditions in the eastern US (Burgan 1988).

The following description of the NFDRS was based from Bradshaw et al (1984), Burgan (1988), and Pyne et al (1996). There are eleven weather parameters that drive the various models of the NFDRS. Parameters observed at the observation time of mid to early afternoon that reflect the worst case scenario include:

United States National Fire-Danger Rating System (NFDRS)

- Air Temperature (F)
- Relative humidity (%)
- State of the weather (cloud cover and type of precipitation)
- Ten-minute average 20-ft windspeed (mph)
- Fuel Stick Moisture (%) – can be measured or estimated

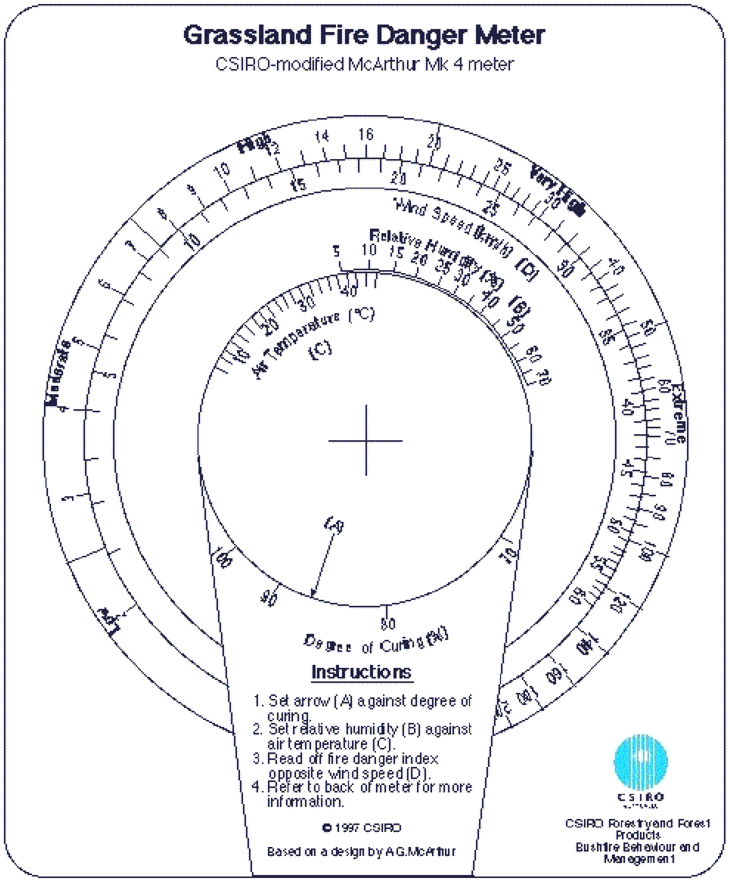

Figure 1. The Grassland Fire Danger Meter (CSIRO 2000).

Daily parameters for the 24-hour period ending at the observation time are:

- Duration of Precipitation (hours)
- Amounts of Precipitation (inches)
- Maximum and Minimum Air Temperature (F)
- Maximum and Minimum Relative Humidity (%)

<u>NFDRS Fire Behavior Components</u>

- Spread Component (SC) – Spread rate, emphasizes 1-hour and 10-hour fuel moisture content
- Energy Release Component (ERC) - Energy Release, emphasizes 100-hour and 1000-hour fuel moisture content
- Burning Index (BI) - flame length or fireline intensity

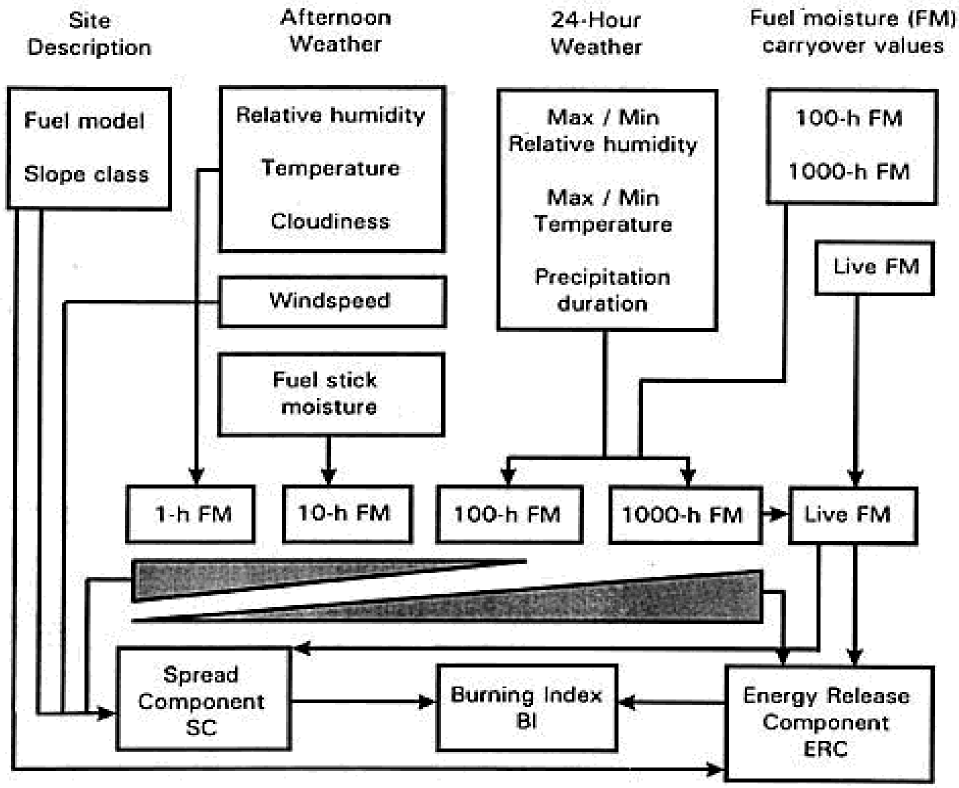

Figure 2. Structure of the US NFDRS showing the relationship between site characteristics, weather, fuel moisture, and final indices (from Andrews and Bradshaw 1997).

In the NFDRS, 20 fuel models representing the following vegetation and fuel types can be selected: annual grass and herbs; perennial grass; sawgrass; open timber/grass; southern rough; sagebrush/grass; mature chaparral; intermediate brush; winter and summer hardwoods; southern plantation; long- and short needled confier; heavy, medium, and light slash; pocosin; Alaskan tundra; and black spruce (Andrews and Bradshaw 1997; Bradshaw et al 1984).

These fuels models are derived by using a combination of dead fuel moisture (1-hour, 10-hour, 100-hour, and 1000-hour) and live moisture (woody and grass) models (Burgan 1988). The moisture content of live fuel and four size classes of dead fuel are calculated from weather data and moisture values. Dead fuel is determined by the diameter of the wood or timelag. The moisture content of the 10-hour fuel is based on observed stick weight. The 1000-hour moisture content is used to calculate the live fuel moisture. In Figure 2, the wedges below the dead fuel moisture boxes indicate the mathematical weighting of the dead fuel moisture content on the various indices. Note that the 1000-hour fuel has no influence on the SC. Windspeed influences the Spread Component (SC), but not the Energy Release Component (ERC).

The NFDRS also has several fire control components: the Man-caused Fire Occurrence Index (MCOI); the Lightning-caused Fire Occurrence Index (LOI); and the Fire Load Index (FLI). However, these components are little used and are designed to be replaced by the lightning ignition potential and lightning on fire danger maps (Latham et al 1997). Presently, a lightning ignition efficiency algorithm by Latham and Schlieter (1989) is being used by the U.S. Wildland Fire Assessment System (WFAS 2000).

NFDRS Applications

The utility of using historical and percentile analysis of fire danger ratings for prescribed natural fire decision making is shown by Andrews and Bradshaw (1995). They state that “a strength of the fire danger rating system is its use in historical calculations" by comparing the current year with past years and the maximum and average values.

Logistic regression, which is designed to handle binary data, is another way to relate fire danger to fire history (Andrews and Bradshaw, 1996). A day can be classified as a fire day (1) or not (0), a multiple fire day (1) or not (0), or as a large-fire day (1) or not (0).

These concepts of analyzing fire danger ratings were developed into a computer program by USDA called FIRES, an acronym for the Fire Information Retrieval and Evaluation System (Andrews and Bradshaw 1997). FIRES provides methods for evaluating the performance of fire danger rating indices. Indices from any fire danger rating system can be used, but the NFDRS is used for the examples. Through logistic regression and percentiles, the program examines the relationship between fire danger indices and historical fire occurrence and size. FIRES helps users choose the appropriate index and fuel model, determine decision levels for an index, and plot and compare historical seasonal trends of fire danger and fire occurrence. An online manual is available for further information at http://www.fs.fed.us/rm/pubs/int_gtr367/ index.html.

Andrews and Bradshaw (1995) discussed methods for using the US NFDRS's Energy Release Component (ERC) to aid fire managers in planning prescribed fires. The 90^{th} or 97^{th} percentile of the ERC has been used to define critical levels of fire danger; the percentiles can be better interpreted if they are related to historical fire occurrences. The fire season can be tracked by plotting and comparing the indices to critical levels, historical average levels, past seasons, and extreme levels. To this end, Andrews and Bradshaw also discussed how the potential fire danger can be calculated into the future for several weeks based on various weather scenarios.

Mees and Bednar (1989) examined fire and weather data from 1970-1984 for northeast Oregon and southern California. They found weak correlations between burned area; the maximum number of personnel used, and the burning index (BI) and energy release component (ERC) of the US NFDRS. However, they did find that the more extreme values of the indices could be used as predictors of extreme fire activity. For example, when the BI was greater than the 90 percentile, fires occurred over 85% of the time in northeast Oregon and 95% of the time in southern California. They suggested that it could be cost-effective to position fire suppression forces to respond quickly in areas of extreme values of the fire indices.

Beyond the U.S., Israel uses danger ratings based on the US NFDRS on a regional basis (Woodcock 1993). The NFDRS has also been adapted for use in South Africa (Van Wilgen 1984)

Oklahoma Fire Danger Model (U.S.)

With the Oklahoma Fire Danger Model, Carlson and Engle (1998) provided a good overview of the next generation of indices that integrate satellite data with a high-density weather station network to produce a fire danger model based on the US NFDRS.

The model calculates live fuel moisture from relative and visual greenness values based on the Normalized Difference Vegetative Index (NDVI) from weekly 1-kilometer resolution Advanced Very High Resolution Radiometer (AVHRR) satellite data. Every kilometer pixel of land has been assigned to a NFDRS fuel model representative of native Oklahoma vegetation. The weekly satellite data are integrated with calculations based from a high-density weather station network (over 100 stations) throughout the state. Hourly NFDRS fire danger indices with a 1-km resolution are produced including the Spread Component (SC); Energy Release Component (ERC); Burning Index (BI); Ignition Component (IC); and dead fuel moisture (FM). From this a daily map of the Keetch-Byram Drought Index (KBDI) is created. For more information see the Oklahoma Fire Danger Model web site at http://agweather.mesonet.ou.edu/ models/fire/default.html.

Canadian Forest Fire Danger Rating System (CFFDRS)

This rating system has been under development since 1968 by the Canadian Forest Service and consists of two modules: The Canadian Forest Fire Weather Index (FWI) System and the Canadian Forest Fire Behavior Prediction System (FBP) System (Stocks et al 1989). The FWI System has been used in Canada since 1970 and consists of six detailed moisture and fire behavior codes that account for the effects of fuel moisture and wind on fire behavior in a standardized fuel type (mature pine stand). The following description of the CFFDRS was based from Stocks et al (1989), Pyne et al (1996), and Van Wagner (1990).

The FBP system will be discussed in the following section on Fire Behavior. The FWI system components need the following daily (noon local standard time) weather parameter inputs:

- Dry-bulb Temperature
- Relative humidity (%)
- 10- meter Wind Speed
- 24 hour cumulative precipitation

<u>FWI System Moisture Components</u>

- Fine Fuel Moisture Code (FFMC) – Numerical rating of the fuel moisture content of fine surface litter and is an indicator of the relative ease of ignition and flammability of fine fuel. Timelag of 2/3 of a day.
- Duff Moisture Code (DMC) - Numerical rating of the average moisture content of loosely compacted organic layers of moderate depth. Timelag of 12 days.
- Drought Code (DC) - Rates the fuel moisture content of deep, compact organic matter. Timelag of 52 days.

Duff is the humus layer on the forest floor consisting of decomposing litter (needles, leaves, and other dead vegetation) and mineral soil. Surface fuel includes standing trees up to 2 meters; herbaceous vegetation (grasses); forest floor litter; and fallen woody material.

The three moisture components are bookkeeping systems that add moisture for rain and subtract moisture for drying. Since the three codes have different timelags, rates, and rain amounts required for saturation, any one of them may be high or low in relation to the others.

<u>FWI System Fire Behavior Components</u>

- Initial Spread Index (ISI) – represents the rate of fire spread
- Buildup Index (BUI) – represents the fuel available for combustion
- Fire Weather Index (FWI) – represents the frontal fire intensity

Figure 3 shows the relationship between the weather inputs and the various components of the FWI system. The FWI, a combination of the ISI and BUI, represents a relative measure of the potential intensity of a single spreading fire with a standard fuel source on level terrain.

The FWI systems components have different interpretations in different fuel types, since the system was developed to represent fire behavior in a generalized, standard fuel type. Each of the components of the FWI system needs to be examined for proper interpretation of past and present fire effects on fuel flammability; each component conveys direct information about certain aspects of wildland fire potential. All of the components of the FWI system are analyzed and displayed at http://fms.nofc.cfs.nrcan.gc.ca /Cwfis/index.html.

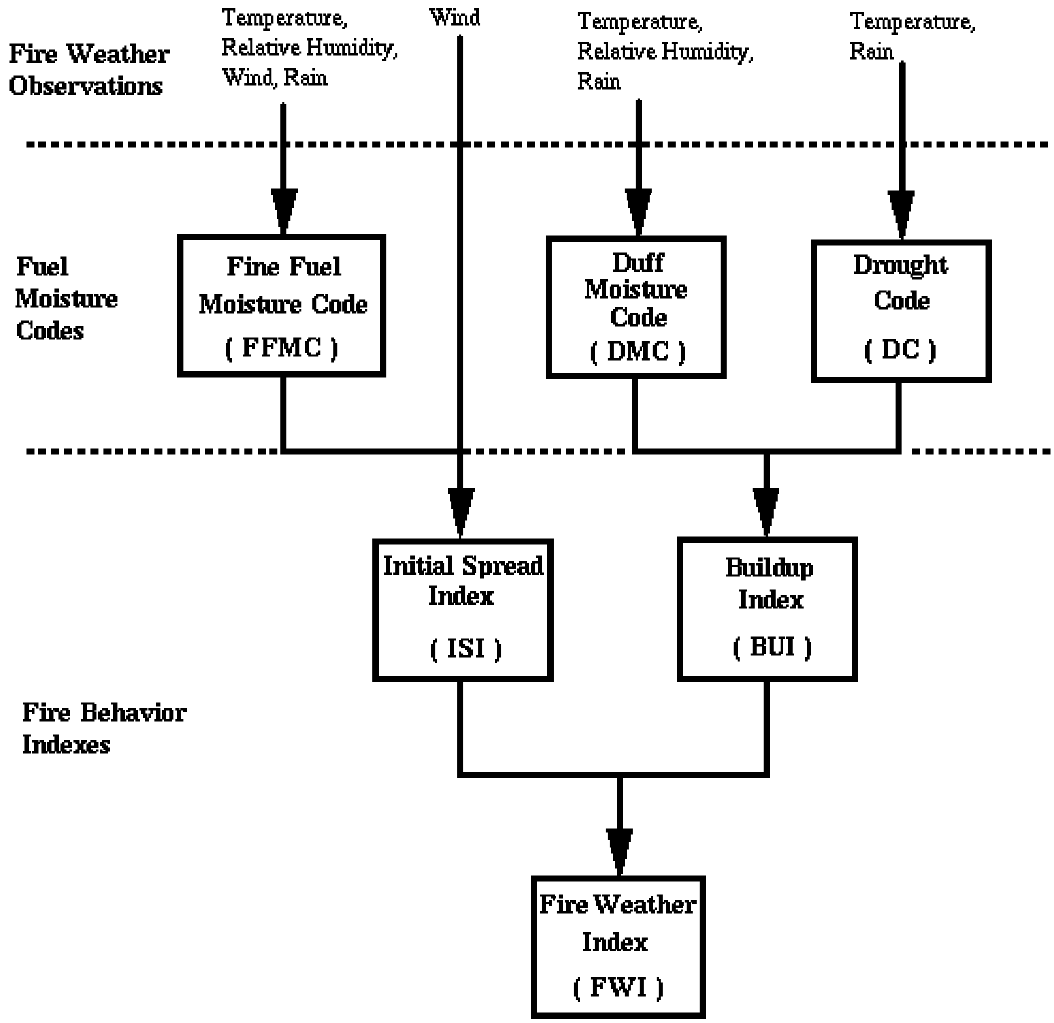

Figure 3. The various components of the Canadian Forest Fire Weather Index System (Canadian Forest Service 1999).

Since the weather varies greatly across Canada, each jurisdiction has developed its own qualitative fire danger classification scheme based on the FWI. The FWI is well suited for the daily representation of fire danger at a particular point but should only be used as a single daily value.

The daily severity rating (DSR) was developed for the temporal and spatial averaging of fire danger for fire management purposes and as a better measure of the work needed to suppress a fire than the FWI (Flannigan and Van Wagner 1991). Van Wagner and Pickett (1985) calculate the DSR from the daily FWI values using the following equation:

$$DSR = 0.0272(FWI)^{1.77} \quad .$$

The DSR can be averaged over a season to produce a seasonal severity rating (SSR) used for comparing fire weather from year to year or place to place (Van Wagner and Picket 1985).

CFFDRS Applications

Stocks et al (1989) states that there are strong correlations between 1) fire occurrence and area burned and 2) the increasing severity of fire weather as reflected by FWI system components. These components are well suited to administrative presuppresion planning. Stocks et al (1989) also cite several specific examples showing strong relationships between man-caused fire occurrence and the Fine Fuel Moisture Code (FFMC), plus a high correlation between area burned and the Initial Spread Index (ISI). The FWI also has been shown to be a good indicator of various aspects of fire activity and is best used as a measure of general fire danger.

The use of the CFFDRS varies throughout Canada depending on the federal or provincial Canadian agency. Some the fire management applications listed by Stocks et al (1989) that include aspects of both the FWI system and the Fire Behavior Prediction (FBP) are:

- Fire behavior training,
- Public prevention planning,
- Preparedness planning,
- Initial Attack dispatching,
- Suppression tactics and strategies,
- Prescribed fire planning.

Natural Resources Canada has been working in conjunction with the Southeast Asia FDRS Project in adapting the CFFDRS for use in Indonesia and Southeast Asia (Southeast Asia FDRS Project 2000). The CFFDRS has been calibrated by adjusting the fuel types and climate for Southeast Asia and Mexico (Canadian Forest Service 1999).

The CFFDRS has also been used in the Daxinganling forest of extreme northern Heilongjiang province in northeastern China, but further calibration is needed to complete implementation (Lynham and Stocks 1989; Yang Yun-Qian and Jin Ji-Zhong 1989).

A modified Canadian Forest FWI system has also been used in New Zealand (Pearce and Alexander 1993).

Comparison of Indices

U.S. and Canadian

The United States and Canadian fire danger rating systems are composed of several different indices that are used for many applications and situations. Both systems can be computed, analyzed, and mapped for various products. There is no single output from these systems and the following discussions will illustrate their uses.

According to Pyne et al (1996), both systems use basically the same daily weather observations, or forecasts to calculate fuel moisture and combine them into similar indices of fire danger. For instance, the SC and ISI relate to spread; the ERC and BUI estimate heat release or available fuel; and the BI and FWI estimate frontal fire intensity. The US NFDRS does, however, require more weather inputs than the FWI System.

The NFDRS models are analytical, based on the physics of moisture exchange, heat transfer, and fire spread. The Canadian models are based on field data from three sources collected over several decades: weather, fuel moisture, and test-fire behavior.

Since the Canadian models are based on observed data they are best applied to the fuel type in which the data were collected. Pyne et al (1996) attributes the difference between the two indices to the differences in training and approaches between the researchers in the United States (engineers) and Canada (foresters).

	US NFDRS	Canadian FWI
Fire Danger	Assumes "worst" case conditions with extreme exposures in the open	Assumes closed forest stand
Fuel Models	20 Fuel Model describing grass, brush, forest, and logging debris	Generalized pine forest with mostly jack pine and lodgepole pine

Table 1. Aspects of the U.S. NFDRS and Canadian FWI system (Pyne et al 1996).

Van Wagner (1975) summarizes that the differences are mainly to the different forest ecosystems of the two countries and states:

> "The American system is probably at its best in the open, grassy forests or brush types with little or no duff layer common in many parts of the United States, but not well represented in Canada. The Canadian system, on the other hand, is at its best in forests with fairly complete canopy and a substantial layer of litter and duff but no marked seasonal variation in herbaceous vegetation."

Van Wagner concludes that due to their technical differences they are providing essentially different kinds of information.

Other Comparisons

Buchholz and Weidemann (2000) compared the Nesterov Index (NI) and the modified KBDI during the 1997 fire season in Indonesia. In general, both indices showed the development of increased fire danger as the season progressed and are useful tools for early warning. A clear limitation of the NI was that it returns to zero given 3 mm of rainfall. In the tropics, 3 mm is too small, since it is not sufficient to saturate the surface duff and vegetation. They suggest that the limit of 3 mm should be increased for use in the tropics. Another limitation of the NI was that it returns to zero with rainfall. This assumes that the fire danger drops to zero for a large area, but due to the high variability in rainfall in the tropics, this assumption is not appropriate for use in fire management.

Buchholz and Weidemann (2000) conclude that the KBDI gives a more realistic overview of fire danger while the NI shows the increased fire risk in periods of extreme drought more dramatically. The advantages of both indices are their simplicity and low data requirements. These make them especially suitable for forest protection in developing countries. They also state that using an network of simple weather stations to provide data for either simple index is preferable to the complex fire danger rating systems of the United States and Canada.

Andrews and Bradshaw (1996) compared different fire danger rating indices in regard to how well the indices reflected the changing fire potential through the fire seasons of 1987 and 1988 at Yellowstone National Park. The 1988 fire season was especially severe, setting new fire records. They specifically examined the Spread Component (SC), Burning Index (BI), and Energy Release Component (ERC) of the US NFDRS and the Keetch-Byram Drought Index (KBDI). The ERC was based on fuel model G which represents a closed, short-needled conifer forest (inc1udes the 1-hour, 10-hour, 100-hour, 1000-hour, and live). The SC and BI did not show a seasonal trend, while the ERC and KBDI showed a seasonal trend and clear differences between the two seasons. The ERC showed a better relationship than the KBDI among percent of fire-days, percent of large-fire days, and logistic regression.

Brown et al (1989) studied the relationship between the actual live moisture content of understory vegetation in the aspen forests of the Western U.S. and estimates from the US NFDRS and KBDI. They found that the NFDRS and KBDI were inconsistent predictors of live moisture content. The KBDI gave reasonable prediction of herbaceous plant moisture during periods of continuous drying but not during summers with significant precipitation.

2.3 FIRE BEHAVIOR PREDICTION

According to Pyne et al (1996), fire behavior can be defined as the dynamics of a specific fire event. Three elements of the fire environment triangle influence fire behavior: Weather, fuel, and topography. Therefore these elements need to be incorporated into any fire behavior prediction system or model. Fire behavior prediction can be considered a combination of art and science that attempts to estimate the spread and intensity of a specific fire; be it for an ongoing fire or a what-if scenario for planning purposes (Pyne et al 1996). The key of fire behavior prediction is linking the analytical calculations from the models to judgements based on experience (i.e. historical analogs). These applications have utility for use in prescribed burning planning and managing unplanning wildfires.

Behave (U.S.)

BEHAVE is a widely used system for fire behavior prediction in the United States. It consists of models for fire spread, moisture, intensity, moisture, and fire size (Pyne et al 1996). It is ideally suited for real-time predictions of wildfire behavior or unplanned ignition prescribed fires (Andrews 1986). The BEHAVE system is composed of two sub-systems: FUEL, the fuel modeling subsystem and BURN, the fire behavior prediction subsystem (Andrews 1986; Andrews and Chase 1989; Burgan and Rothermel 1984). BEHAVE system inputs are user-supplied; some of the requested values depend upon the modeling choices made by the user.

Andrews (1986) lists several applications for the BEHAVE system: initial attack dispatch; wildfire prediction; prescribed fire planning; fire effects; projection of an ongoing fire; fuel hazard assessment; fire prevention planning; and training.

Andrews and Chase (1990) cite several specific examples of some these applications of the BEHAVE system. The BEHAVE system was first used on fire in Montana in 1984 and correctly predicted that the fire would stay within a wilderness area and not threaten people or property. Fire managers used BEHAVE to support their position that intense fire suppression was not needed, therefore saving an estimated $750,000.

In another example, two California National Parks used BEHAVE to help make prescribed burning decisions. Based on BEHAVE predictions, areas of the parks were classified as either natural fire zones or as areas to be burned to reduce fuel accumulation and fire hazard. This resulted in significant savings by reducing the need for prescribed fire.

Other examples include using the BEHAVE system to help calculate dead fuel contents during the 1988 Yellowstone fires and to determine whether a spot fire observed during a prescribed burn was caused by the main fire or a lightning strike.

The BEHAVE system has been updated into a new graphical interface and computer program called Behaveplus (Andrews and Bevin 1998). Behaveplus has the same models as in BEHAVE such as: surface fire spread; intensity, flame length; area and perimeter of a point source fire; spotting distance; probability of ignition; scorch height; and tree mortality.

De Ronde (1999) describes developing an unique set of fuel models for several forest regions in South Africa for input into BEHAVE. This was used for predicting fire hazard rating and at arriving at more realistic fire protection requirements.

For further information on BEHAVE and other models see the web site at http://www.fire.org/perl/ tools.cgi#BEHAVE.

Canadian Forest Fire Behavior Prediction System (FBP)

The Canadian Forest Fire Behavior Prediction System (FBP) is the second major subsystem of the CFFDRS. The FBP is based on field data of readily measured variables on over 400 experimental fires and well-documented prescribed and wildland fires (Stocks et al 1989). The FBP system is based partly on the FWI system and hourly fire weather observations (see Figure 4). It provides quantitative outputs of selected fire behavior characteristics for Canadian fuel types and topography (Hirsch 1996).

The system has 16 fuel types including: spruce-lichen woodland; boreal spruce; immature and mature jack/lodgepole pine; red and white pine; conifer plantation; ponderosa pine/douglas fir; leafless aspen; green and leafless boreal mixedwood; green and leafless dead balsam fir mixedwood; jack/lodgepole pine slash; spruce/balsam slash; coastal cedar/hemlock/douglas-fir slash; and grasses.

McAlpine and Xanthoplouos (1989) have made a comparison of the FBP and the American BEHAVE fire behavior prediction system. They find that the Canadians used an empirical approach in designing a fire behavior prediction system while the Americans developed an adaptable theoretical model.

By conducting 17 experimental fires in a wind tunnel, McAlpine and Xanthoplouos collected data on the head fire rate of spread (ROS). They concluded that the American BEHAVE system consistently under-predicted observed ROS by 15-60%, while the Canadian FBP system over-predicted observed ROS. The most influential factor for the prediction errors was the wind speed and associated wind profile above the fuel. Significantly, ROS is very sensitive to changes in wind speed: the effectiveness of any fire behavior prediction system depends upon the accuracy of the fire site wind information.

Hirsch (1989) examined both the measured and the FBP predicted rate of spread of several wildfires in southern Manitoba in 1988. While the FBP predictions were similar for some fires, for others there were considerable under- and over-estimations. A variety of factors caused errors in calculating fire rate of spread values such as the variations in fuel type and spatial differences in weather parameters.

However, Hirsch (1989) concluded that, to ensure reliable fire behavior predictions, input variables, especially wind speed, must be accurately measured at or very close to the fire sire on a near-real time basis. Additionally, Hirsch found that the weather reported from a given station may not be representative of the conditions at the fire site. Given that windspeed measurements are extremely variable and may not be representative from area to area, the use of mesoscale models may improve the utility of the fire behavior models.

Sirofire (Australia)

In Australia, the CSIRO's Bushfire Behavior and Management Group developed a Bushfire Spread Simulator called SiroFire (CSIRO 1997). Sirofire was constructed around the McArthur fire danger rate system meters and the new Grassland Fire Spread Meter. According to CSIRO (1997), Sirofire, unlike the meters, estimates the rate of spread for the entire perimeter of interest. It has an easy-to-use interface and uses GIS-derived geographic maps and digital terrain models to graphically present maps of the spread of fire. It is a DOS based program that runs in a Windows-like user interface and has been used as an operational and training tool by the South Australian Country Fire Service (Coleman and Sullivan 1996).

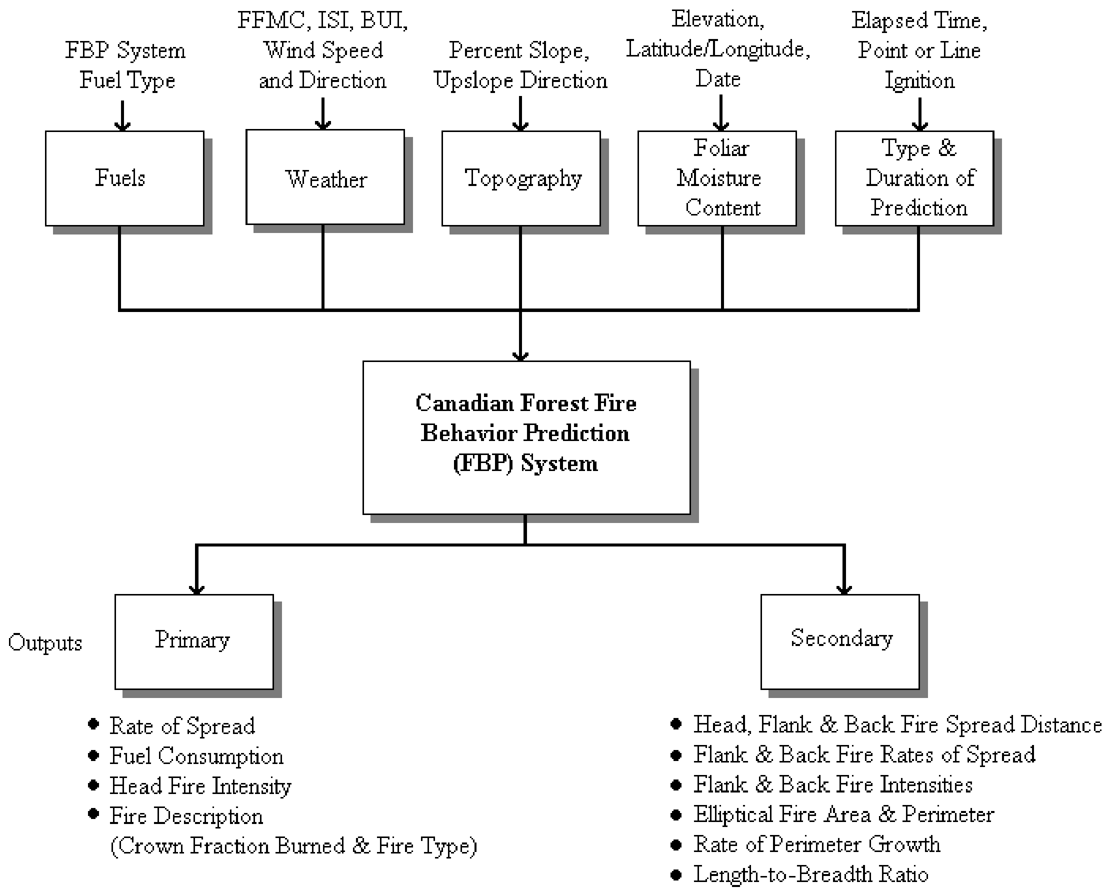

Figure 4. Inputs, outputs, and structure of the Canadian Forest Fire Behavior Prediction System (Canadian Forest Service 1999).

2.4 ATMOSPHERIC INDICES

Lavdas (1986) states that the range of weather conditions acceptable for prescribed burning also overlap with the good dispersion of pollutants. Therefore, with proper management neither the smoke or the fire will be a hazard. The atmospheric indices discussed below were developed to aid in planning and scheduling prescribed fires.

Haines (1988) developed a Lower Atmospheric Severity Index (LASI) for wildland fires based on the atmospheric lapse rate of a layer of air (its measure of stability) coupled with its moisture content. The index was partitioned in three versions: a low (eastern United States), mid (Great Plains and Appalachian Mountains), and high (western US) elevation. The index is also referred to as the Haines Index and is composed of two terms (Haines, 1988; Werth and Ochoa, 1990):

$$
\begin{aligned}
\text{LASI} &= \text{stability} + \text{moisture} \\
&= (T_{p1} - T_{p2}) + (T_p - T_{dp}) \\
&= A + B
\end{aligned}
$$

where T is the temperature at two pressure surfaces (p1 , p2); T_p and T_{dp} are the air temperature and dew-point temperature at one of the levels. Table 2 shows the limits of the indices at the three elevations.

Elevation	Stability term (A)	Moisture term (B)
Low	**950-850 mb °T** 1 when 3 °C or less 2 when 4-7 °C 3 when 8 °C or more	**850 mb °T – 850 mb dewpoint** 1 when 5 °C or less 2 when 6-9 °C 3 when 10 °C or more
Mid	**850-700 mb °T** 1 when 5 °C or less 2 when 6-10 °C 3 when 11 °C or more	**850 mb °T – 850 mb dewpoint** 1 when 5 °C or less 2 when 6-12 °C 3 when 13 °C or more
High	**700-500 mb °T** 1 when 17 °C or less 2 when 18-21 °C 3 when 22 °C or more	**850 mb °T – 850 mb dewpoint** 1 when 14 °C or less 2 when 15-20 °C 3 when 21 °C or more

Table 2. Stability and moisture limits of the low-, mid-, and high-elevation indices (from Werth and Ochoa, 1990).

The LASI scale for indicating potential for large fire growth is:

- 2 or 3: Very low potential (moist stable lower atmosphere)
- 4: Low Potential
- 5: Moderate Potential
- 6: High Potential (dry unstable lower atmosphere)

Werth and Ochoa (1990) compared the LASI to burned acreage in a portion of the western U.S. from July to September 1990. The LASI was 6 on 6% of the days, during which over 75% of the acreage burned. They concluded that LASI values of 5 or 6, the probability of extreme fire behavior significantly increases, while fire behavior is usually low with values 4 or less. Additionally, the LASI is best suited for plume-dominated fires, which are fires where the power of the fire is greater than the power of the wind.

Werth and Werth (1998) studied the Haines Index (LASI) across the western U.S. and concluded that the index shows more utility than traditional stability indices in predicting large wildfire growth and extreme fire behavior. Moreover some refinement is needed.

Lavdas (1986) developed the Dispersion Index (DI) to estimate the atmospheric capacity to disperse smoke from prescribed burning activities. The DI scale ranges from 1 (very poor) to over 100 (very good) and represents weather conditions over a 6-hour period. The index represents the inverse of the estimated smoke concentration for a hypothetical 50 by 50 km area. This index is based on the day and night Pasquill-Gifford-Turner (PGT) stability class, mixing height, and transport windspeed. The inputs for the Pasquill-Gifford-Turner (PGT) stability class are solar elevation angle; surface windspeed; opaque cloud cover; and cloud ceiling height.

For more information about the Pasquill-Gifford-Turner (PGT) stability class see Weil (1988) and Appendix A of Lavdas (1986). The Canadian Forest service makes daily analyses of the DI and the Pasquill-Gifford-Turner (PGT) stability class on their web site for forest managers at http://fms.nofc.cfs.nrcan.gc.ca/ cwfis/index.html.

2.5 FOREST YIELD/PRODUCTIVITY MODELS

Sands et al (2000) writes that forest yield and productivity models are used to help forest managers answers questions about climate change, ecological succession, and yield prediction. However, the application of these models to stand management is just beginning.

Many forest yield/productivity models, too numerous to be discussed here, have been developed that are species-specific. The models surveyed in this section are relatively current and easy to use process models that can be used for sustainable forest management.

Kimmins (1990) provides a review of the historical progression of forest growth and yield models. Historical bioassay was the standard method of forest yield prediction. Formalized by German foresters in the late 1700s and is comprised of the forward projection of past patterns of forest growth: by measuring past growth of forest stands at a site or region, one can predict future growth and yield. However, Kimmins (1990) argues that these methods only work if future growing conditions are similar to the past conditions under which the measurements were taken. Therefore, the historical bioassay method would not be suitable for yield prediction if the future growing conditions are not the same as the past. This raises problems with the historical bioassay method especially given the concern about climate change and global warming.

Kimmins (1990) goes on to discuss detailed process-based models but concludes that the best approach may be a hybrid simulation approach that is a combination of the historical bioassay approach and process-based models. In a chapter entitled "Models and Their Role in Ecology and Resource Management", Kimmins (1997) lists over 30 such types of models based on these principles.

Landsberg and Waring (1997) and Landsberg et al (2001) describe a relatively simple growth model called Physiological Principles in Predicting Growth, or 3-PG for short. This model is based on well-established principles, can be easily parameterized for particular forest types, and uses monthly inputs and time steps. Weather inputs are:

- Monthly total short-wave incoming radiation
- Monthly mean day-time vapor pressure deficits
- Total monthly precipitation
- Number of days per month with frost
- Average Temperature

Additional inputs include: initial biomass values of foliage, stems, and roots; soil water and type parameters; stand age and maximum stand age; and several parameter values related to photosynthesis. Monthly or annual outputs include: leaf area index, stem mass, volume, and number; stem growth rate; and mean annual increment.

In general, this model calculates gross primary production from a linear relationship between absorbed photosynthetically active radiation (PAR) and canopy carbon fixation. This process is regulated by atmospheric humidity and stomatal conductance as well by air temperature, water balance, and nutrition. Monthly transpiration is calculated from the Penman-Monteith equation. The net primary production is calculated from a simple ratio based on gross primary production and is then allocated to roots, stems, and foliage. Allocation to the stems and foliage relies on allometric equations describing leaf and stem mass. These allometric parameters may vary with species and are the most important parameters in the model. 3-PG has to be calibrated by fitting observed foliage parameters with weather data and estimated soil water holding capacity and fertility. Calibrations based at one site can be used to predict growth at other sites. It has been developed for use in a spreadsheet and in the Visual Basic programming language.

The 3-PG model showed an excellent correlation between measured and simulated stem growth for pine trees grown at two sites in New Zealand (Landsberg and Waring 1997). Landsberg et al (2001) also tested the model against loblolly pine data from North Carolina, USA. One set of unfertilized experimental test plots was used to calibrate the model; then, the effects of simulated fertilization were tested. They found excellent to good correlations between several simulated and measured growth parameters. They then used this calibrated version on an independent set of plots to test the model. They found the model can accurately simulate the behavior and responses to environmental factors of loblolly pine. It has considerable potential as a management, scenario analysis, and research tool.

Coops et al (1998) adapted the 3-PG model to be used with satellite derived data. They used the Normalized Difference Vegetation Index (NDVI) to obtain estimates of the fraction of PAR absorbed by the forest canopy. Adjusting this measurement for the slope and aspect of land units, in combination with weather and soil data, can produce estimates of the net primary production of the forests.

FOREST-BGC is another forest ecosystem process model described by Running and Coughlin (1988). This model calculates carbon, water, and nitrogen cycles in a forest ecosystem and uses the leaf area index to determine important forest structure for energy and mass exchange. Daily weather inputs include:

- Maximum and minimum air temperature
- Precipitation
- Dewpoint; can be estimated by minimum temperature if unavailable
- Soil temperature; can be estimated by maximum and minimum temperatures if unavailable
- Short-wave radiation; can be derived if unavailable

The FOREST-BGC model simulates hydrology, photosynthesis, transpiration, and net primary production and the results compared reasonably well documented field data, but a site-specific validation has not been done.

Sands et al (2000) developed a simple process-based plantation productivity model, PROMOD, for use as a basis for decisions on forest management. The input data, which can be inexpensively obtained, includes: latitude; slope and stand density; soil characteristics; monthly mean daily maximum and minimum temperatures; solar radiation; rainfall; pan evaporation; and number of days of rain. Outputs include: net primary production; peak mean annual increment; LAI; evapotranspiration; and light-use efficiency.

The model has produced good predictions of site productivity for eucalytpus in Tasmania and Western Australia.

For more information on the current state of the art process-based models see Makela et al (2000) and for some applications of forest productivity related to remote sensing see Gholz et al (1997).

2.6 CLIMATE CHANGE

The paper by Flannigan and Van Wagner (1991) will be discussed in detail because it illuminates several aspects of using the monthly output of general circulation models (GCM) to assess impacts on daily indices.

Flannigan and Van Wagner (1991) examined the impact of potential greenhouse warming on the severity of the forest fire season in Canada. Six stations across Canada were selected representing a variety of climate and forests. They calculated the daily severity rating

(DSR) from Canadian Forest Fire Index System based on daily weather data from 1953-1987. The DSR's from May to August were averaged into seasonal severity ratings (SSR) that were used as a measure of forest fire season severity. They then selected those years that had the highest and lowest SSR, along with a year with a SSR near the mean. These 18 SSR's represented a base line of forest fire severity. They used the simulation output that doubled the CO_2 levels (2 X CO_2) of three general circulation models (GCM): Geophysical Fluid Dynamics Laboratory (GFDL), Goddard Institute for Space Studies (GSS) and Oregon State University (OSU). Gridded monthly anomalies were calculated by the difference between the 2 X CO_2 case. The 1 X CO_2 (present) case for temperature and precipitation anomalies were determined by the 2 X CO_2 case divided by the 1 X CO_2 (present) case. However, the cases representing a climate with double the CO_2 had to be transformed into the DSR's from which the SSR's are calculated. They assumed that the historical daily weather patterns and variability would remain the same. The anomalies were superimposed on the three sets of daily weather data in the following manner:

- Monthly temperature anomalies were added to each daily temperature
- Monthly precipitation anomalies were multiplied to the daily precipitation (if any)
- Relative humidity was recalculated based on the new temperature and the old dewpoint
- Windspeeds remained unchanged

The authors found that higher temperatures alone caused significant increases in the SSR's for the 2 X CO_2 scenario. Temperatures increased and the dewpoints remain unchanged, causing the relative humidity to decrease, increasing the SSR's. Thus, the authors suggested that holding the relative humidity constant may more accurately represent the daily weather in a warmer climate.

They also argue that assuming that the windspeed will not change may also be unrealistic. The predicted precipitation anomalies had little impact on the SSR's. This was due to the fact the models differed on their predictions (increasing or decreasing precipitation in different regions) and that the frequency of rainfall was not changed. The monthly area burned in Canada is strongly influenced by long periods of dry weather, therefore the frequency of rainfall is more important than the cumulative rainfall. The study of Flannigan and Van Wagner (1991) concludes that in a 2 X CO_2 climate scenario, there is a 46% increase in the SSR and a 40% increase in the burned area in Canada. They go on to state, however, that the SSR is only one factor affecting burned area. The other two are ignition frequency and fire control activity.

2.7 SMOKE MANAGEMENT AND AIR QUALITY

Fox et al (2000) specifically discuss the conflict between the ecological and practical benefits to forests of prescribed fires and the potential negative health and visibility consequences of smoke. In the U.S. in the late 1990's, stricter national ambient air quality standards required forest fire managers to manage smoke more stringently. Yet, the problem of smoke is globally pervasive. Pyne et al (1996) writes that during 1983 and 1997/98, Indonesia suffered from severe El-Niño related droughts due to poor management practices, and led to large fires in East Kalimantan, Borneo. Specifically, a migration of settlers to large-scale rural logging sites used fire to clear the land, but there was no institutional mechanism for fire control. These Boreno fires produced smoke that blanketed parts of Southeast Asia, shutting down airports as far away as Singapore. Since then Indonesia has received aid from several countries to develop their fire management capabilities. Therefore, smoke management techinques must be developed and disseminated globally.

One source of relevant smoke applications for forestry comes from the Technically Advanced Smoke Evaluation Tools (TASET) Workshop held at Colorado State University during February 2-4, 2000. This workshop was attended by smoke management experts from across the U.S., who recommended the following models for use and further development (Fox and Riebau 2000).

The Simple Approach Smoke Estimation Model (SASEM) was developed by the U.S. Bureau of Land Management for estimating whether or not smoke from a prescribed fire will exceed air quality standards on federal lands (Sestak and Riebau 1988). It is the tool of choice in the U.S. for receiving approval from local regulators to conduct a prescribed burn based on air quality (Fox et al 2000). It is currently used by the states of Wyoming, Colorado, Arizona, New Mexico, and Idaho as a regulatory tool (Fox and Riebau 2000). From Sestak and Riebau (1988), the SASEM single point weather inputs are:

- Average Mixing Height
- Stability Class (Dispersion Day)
- Wind Direction range
- Maximum and Minimum Wind Speed

Other inputs include the date, size, and duration of the fire; fire line intensity; fuel arrangement; type and load; and direction and distance from fire to receptor (highways or residential areas). Important outputs include emission rates; total particles emitted; exceedence of air quality standards; plume height; and visibility ranges. The model uses a straight-line trajectory Gaussian plume for plume dispersion (Breyfogle and Ferguson 1996). The easy to use model was designed for federal land managers, can be used on a DOS PC, but for only one fire at a time. The TASET workshop recommends that SASEM be upgraded and approved as a national smoke management screening tool (Fox and Riebau 2000).

The other models recommended by TASET are more complex grid models. CalMet/CalPuff is a combined meteorological and dispersion models system that can address multiple fires and complex terrian. The model system has received regulatory acceptance (Fox and Riebau 2000). It uses a variable trajectory Gaussian puff plume dispersion, takes into account the air chemistry of SOx and NOx, but needs a 486DX CPU PC running Windows with at least 10 MB of disk space, and 4 MB minimum of memory (Breyfogle and Ferguson 1996).

2.8 RELEVANT WEB PAGES

Australian CSIRO Bushfire Behavior and Management Home Page
http://www.ffp.csiro.au/nfm/fbm/index.html

Canadian Forest Service Home Page
http://fms.nofc.cfs.nrcan.gc.ca/

Indonesian Fire Danger Rating System
http://www.fdrs.or.id

International Forest Fire News published by the Joint FAO/ECE/ILO Committee on Forest Technology, Management and Training
http://www.uni-freiburg.de/fireglobe/iffn/iffn.htm

USDA Forest Service's Wildland Fire Assessment System
http://wfas.net/cgi-bin/nav.cgi

USDA Online Fire Software and Information Systems
http://www.fire.org/

2.9 REFERENCES:

Alexander, M. E. 1990. Computer calculation of the Keetch-Byram drought index – programmers beware! *Fire Management Notes*. 51(4):23-25.

Andrews, P. L. 1986. BEHAVE: fire behavior prediction and fuel modeling system: BURN subsystem, Part 1. General Technical Report. INT-194. Ogden, UT. US Department of Agriculture, Forest Service, Intermountain Research Station. 130 p.

Andrews, P. L. and C. D. Bevin. 1998. Update and expansion of the BEHAVE fire behavior prediction system. http://www.firelab.org/pdf/fbp/pandrews/update.pdf.

Andrews, Patricia L. and Bradshaw, Larry S. 1995. Fire danger rating and the go/no-go decision for prescribed natural fire. Symposium on Fire in Wilderness and Park Management: past Lessons and Future Opportunities; 1993 March 30-April 1; Missoula MT. General Technical Report. INT-GTR-320. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 149-151.

Andrews, Patricia L. and Bradshaw, Larry S. 1996. Interpretation of the National Fire Danger Rating System for Yellowstone National Park. Symposium on ecological implications of fire in Greater Yellowstone. 1993 September 19-21:211-216. http://www.firelab.org/pdf/fbp/ pandrews/interp.pdf.

Andrews, Patricia L. and Bradshaw, Larry S. 1997. FIRES: Fire Information Retrieval and Evaluation System - a program for fire danger rating analysis. General Technical Report INT-GTR-367. Ogden, UT; U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 64 p. http://www.fs.fed.us/rm/pubs/int_gtr367/ index.html

Andrews, Patricia, L. and C. H. Chase. 1989. BEHAVE: fire behavior prediction and fuel modeling system: BURN subsystem, Part 2. Gen. Tech. Rep. INT-260. Ogden, UT. US Department of Agriculture, Forest Service, Intermountain Research Station. 93 p.

Andrews, P. L. and C. H. Chase. 1990. The BEHAVE fire prediction system. *Fire Management Notes.* Winter 1990: 4-9.

Baier, W., R. Gommes, and M. V. K. Sivakumar. 1999. Agrometeorology and Sustainable Agriculture. *World Meteorological Organization Bulletin.* 48(4): 374-379.

Bradshaw, Larry S., John E. Deeming, Robert E. Burgan, Jack D. Cohen. 1984. The 1978 National Fire-Danger Rating System: Technical Documentation. Gen. Tech. Rep. INT-169. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station: 44p.

Breyfogle, S. and S. A. Ferguson. 1996. User assessment of smoke-dispersion models for wildland biomass burning. Gen. Tech. Rep. PNW-GTR-379. Portland, OR. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 30 p.

Brown, J. K., G. D. Booth, and D. G. Simmerman. 1989. Seasonal change in live fuel moisture of understory plants in western U.S. aspen. Pages 406-412 *in* Proceedings of the 10th Conference on Fire and Forest Meteorology, 17-21 April 1989. Ottawa, Canada.

Buchholz, G. and D. Weidemann. 2000. The use of simple fire danger rating systems as a tool for early warning in forestry. FAO/ECE/ILO International Forest Fire News. No. 23. p 33-36. http://www.uni-freiburg.de/ fireglobe/iffn/iffn_23/content.htm

Burgan, R. E. 1988. 1988 Revisions to the 1978 National Fire-Danger Rating System. Res. Pap. SE-273. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 39p.

Burgan, R.E., Rothermel, R.C. 1984. BEHAVE: fire behavior prediction and fuel modeling system-FUEL subsystem. Gen. Tech. Rep. INT-167. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 126 p.

Canadian Forest Service. 1999. Canadian Wildland Fire Information System. Natural Resources Canada. Available at http://fms.nofc.cfs.nrcan.gc.ca/cwfis/index.html.

Carlson, J. D. and D. M. Engle. 1998. Recent developments in the Oklahoma fire danger model, a mesoscale fire danger rating system for Oklahoma. Pages 42-47 *in* Preprints of the 2nd Symposium on Fire and Forest Meteorology, Phoenix, Arizona. January 11-16, 1998. Amercian Meteorological Society, Boston, MA.

Cheney, P. and Sullivan, A. 1997. *Grassfires: Fuel, Weather and Fire Behaviour*. CSIRO Publishing, Melbourne 102 pp.

Coleman, J.R. and Sullivan, A.L. 1996. A real-time computer application for the prediction of fire spread across the Australian landscape. *Simulation* **67**(4): 230-40.

Coops, N. C., R. H. Waring, and J. J. Landsberg. 1998. Assessing forest productivity in Australia and New Zealand using a physiologically-based model driven with averaged monthly weather data and satellite-derived estimates of canopy photosynthetic capacity. *Forest Ecology and Management*. 109: 113-127.

Commonwealth Scientific and Industrial Research Organization (CSIRO). 1997. SiroFire: The CSIRO Bushfire Spread Simulator. http://www.ffp.csiro.au/nfm/fbm/sirofire/sirofire.html

Commonwealth Scientific and Industrial Research Organization (CSIRO). 2000. The CSIRO grassland fire danger and fire spread meters. http://www.ffp.csiro.au/nfm/fbm/grassmet.html

Deeming, John E., J. W. Lancaster, Michael A. Fosberg, William R. Furman, Mark J. Schroeder. 1972. The National Fire-Danger Rating System. Research Paper RM-84. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. Revised 1974. 165 p.

De Ronde, N. 1999. Integrated Fire Management in Southern Africa. FAO/ECE/ILO International Forest Fire News. No. 21. p 17-21. http://www.uni-freiburg.de/fireglobe/iffn/country/za/za_11.htm

Flannigan, M. D. and C. E. Van Wagner. 1991. Climate change and wildfire in Canada. Canadian Journal of Forest Research. 21: 66-72.

Fosberg, M.A., B. J. Stocks, and T. J. Lynham. 1996. "Risk Analysis in Strategic Planning: Fire and Climate Change in the Boreal Forest", Fire in Ecosystems of Boreal Eurasia. Volume 48 of Forestry Sciences. Ed. J. G. Goldammer and V. V. Furyaev. Kluwer Academic Publishers. 494-505.

Fox, D. G, A. R. Riebau, and R. W. Fisher. 2000. Managing Smoke in United States Wildlands and Forests: A challenge for science and regulations. *In* Biomass Burning and its inter-Relationships with the Climate System (J. L. Innes , M. Beniston, and M. V. Vertraete ed.). Kluwer Academic Publishers.

Fox, D. G. and A. R. Riebau. 2000. Final Report: Technically Advanced Smoke Evaluation Tools (TASET). Cooperative Institute for Research in the Atmosphere (CIRA), Colorado State University. 99 p. http://www.cira.colostate.edu/smoke/TASETfinal REPORT.pdf

Fujioka, F. M. 1991. Starting up the Keetch-Byram Drought Index. Proceeding of the 11th Conference on Fire and Forest Meteorology, April 16-19, 1991. p 74-80.

Gill, A. M., K. R. Christian, P. H. R. Moore, and R. I. Forrester. 1987. Bushfire incidence, fire hazard and fuel reduction burning. Australian Journal of Ecology 12:299-306.

Gholz, H. L., K. Nakane, and H. Shimoda. 1997. The Use of Remote Sensing in the Modeling of Forest Productivity. Kluwer Academic Publishers. Dordrecht, The Netherlands.

Haines, D. A., W. A. Main, J. S. Frost, and A. J. Simard. 1983. Fire-danger rating and wildfire occurrence in the Northeastern United States. *Forest Science*. 29(4): 679-696.

Haines, D. A. 1988. A lower atmospheric severity index for wildland fire. National Weather Digest. Vol. 13. No. 2:23-27.

Hall, J. B. and W. N. K. Gwalema. 1985. Drought indices and fire danger indices at Morogoro, Tanzania. Forest Ecology and Management. 10:125-134.

Hirsch, K. G. 1989. Analysis of the fire behavior associated with three 1988 spring wild fires in central Canada. Pages 416-425 *in* Proceedings of the 10th Conference on Fire and Forest Meteorology, (D. C. Maciver, H. Auld, and R. Whitewood, ed.). Ottawa, Canada April 17-21, 1989.

Hirsch, K. G. 1996. Canadian Forest Fire Behavior Prediction (FBP) System: user's guide. Special Report 7. Canadian Forest Service, Northwest Region, Northern Forestry Centre.

Juhnke, S. R. and R. F. Fuggle. 1987. Predicting weather for prescribed burns in the South-Western Cape, Republic of South Africa. South African Forestry Journal. 142:41-46.

Keetch, John, J and George M. Byram. 1968. A drought index for forest fire control. Res. Paper SE-38. Asheville, NC: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 32p.

Kimmins, J. P. 1990. Modelling the sustainability of forest production and yield for a changing and uncertain future. *The Forestry Chronicle.* 66(3): 271-280.

Kimmins. J. P. 1997. Forest Ecology: A Foundation for Sustainable Management. Prentice Hall, Upper Saddle River, New Jersey, USA.

Landsberg, J. J. and R. H. Waring. 1997. A generalized model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *Forest Ecology and Management.* 95: 209-228.

Landsberg, J.J., K. H. Johnsen, T. J. Albaugh, H. L. Allen, and S. E. McKeand. 2001. Applying 3-PG, a simple process-based model designed to produce practical results, to data from loblolly pine experiments. *Forest Science*. 47(1): 43-51. http://www.srs.fs.fed.us/pubs/rpc/2001-04/rpc_01apr_05. pdf

Latham, Don J. and Joyce A. Schlieter. 1989. Ignition probabilities for wildland fuels based on simulated lightning discharges. Res. Pap. INT-411. Ogden, UT. US Department of Agriculture, Forest Service, Intermountain Research Station. 16p.

Latham, Don J., Robert Burgan, Carolyn Chase, and Larry Bradshaw. 1997. Using Lightning Location in the Wildland Fire Assessment System. Gen. Tech. Rep. INT-GTR-349. Ogden, UT. US Department of Agriculture, Forest Service, Intermountain Research Station. 5 p.

Lavdas, L. G. 1986. An atmospheric dispersion index for prescribed burning. USDA Forest Service. Southeastern Forest Experiment Station. Research Paper SE-256. 33 p.

Lynham, T. J. and B. J. Stocks. 1989. Suitability of the Canadian Forest Fire Danger Rating System for use in the Daxinganling Forestry Management Bureau Heilongjiang Province, China. Pages 232-246 *in* Proceedings of the 10th Conference on Fire and Forest Meteorology, (D. C. Maciver, H. Auld, and R. Whitewood, ed.). Ottawa, Canada April 17-21, 1989.

Makela, A., J. Landsberg, A. R. Ek, T. E. Burk, M. Ter-Mikaelian, G. I. Agren, C. D. Oliver, and P. Puttonen. 2000. Process-based models for forest ecosystem management: current state of the art and challenges for practical implementation. *Tree physiology*. 20(5/6): 289-298.

McAlpine, R. S. and G. Xanthopoulos. 1989. Predicted vs Observed Fire Spread Rates in Ponderosa Pine Fuel Beds: A test of American and Canadian Systems. Pages 287-294 *in* Proceedings of the 10th Conference on Fire and Forest Meteorology, (D. C. Maciver, H. Auld, and R. Whitewood, ed.). Ottawa, Canada April 17-21, 1989.

McArthur, A. G. 1966. Weather and grassland fire behavior. Commonwealth of Australia Forestry and Timber Bulletin Leaflet 100. 23 p.

McArthur, A. G. 1967. Fire Behavior in eucalypt forest. Commonwealth of Australia Forestry and Timber Bulletin Leaflet 107. 32 p.

Mees, R. and L. Bednar. 1989. The use of fire weather indices in the prediction of extreme fore loads. *Journal of Applied Western Forestry.* 4(2):46-48.

Noble, I. R. G. A. Bary, and A. M. Gill. 1980. McArthur's fire-danger meters expressed as equations. *Australian Journal of Ecology* 5:201-203.

Pearce, H. G. and M. E. Alexander. Fire Danger Ratings associated with New Zealand's major pine plantation wildfires. Pages 534-543 *in* Proceedings of the 12th Conference on Fire and Forest Meteorology. Jekyll Island, Georgia. October 26-28, 1993.

Pyne, Stephen J., Patricia L. Andrews, and Richard D. Laven. 1996. Introduction to Wildland Fire. John Wiley and Sons. 769 p.

Running, S. W. and J. C. Coughlan. 1988. A general model of forest ecosystem processes for regional applications I. Hydrologic balance, canopy exchange and primary production processes.

Sands, P.J., M. Battaglia, and D. Mummery. 2000. Application of process-based models to forest management: experience with ProMod, a simple plantation productivity model. *Tree physiology*. 20(5/6): 383-392.

Sestak, M. L. and A. R. Riebau. 1988. SASEM simple approach smoke estimation model. Technical Note 382. Denver, CO: U.S. Department of the Interior, Bureau of Land Management. 31 p.

Solibun, H. and P. Lagan. 1998. Fire Management Plan: Deramokot Forest Reserve. Deramokot Forest Reserve, Sabah, Malaysia. Available at http://www.sabah.gov.my/htan/ENGLISH/IN_FILES/ document/ DFRForestFire.pdf

Southeast Asia FDRS Project. 2000. Indonesia FDRS Report. Southeast Asia Fire Danger Report System Project – FDRS Report No. 1. http://www.fdrs.or.id/newsletters/newsletter_current.pdf.

Stocks, B. J, B. D. Lawson, M. E.Alexander, C. E. Van Wagner, R. S. McApline, T. J. Lynham, and D. E. Dube. 1989. The Canadian Forest Fire Danger Rating System: An Overview. *The Forestry Chronicle.* 65(6):450-457.

Stocks, B. J., D. R. Cahoon, J. S. Levine, W. R. Cofer III, and T. J. Lynham. 1996. "Major 1992 Forest Fires in Central and Eastern Siberia: Satellite and Fire Danger Measurements", Fire in Ecosystems of Boreal Eurasia. Volume 48 of Forestry Sciences. Ed. J. G. Goldammer and V. V. Furyaev. Kluwer Academic Publishers. 139-150.

Stocks, B. J. and T. J. Lynham. 1996. "Fire Weather Climatology in Canada and Russia", Fire in Ecosystems of Boreal Eurasia. Volume 48 of Forestry Sciences. Ed. J. G. Goldammer and V. V. Furyaev. Kluwer Academic Publishers. 481-487.

Van Wagner, C. E. 1975. A comparison of the Canadian and American forest fire danger rating systems. Information Report PS-X-59. Petawawa Forest Experiment Station. Chalk River, Ontario.

Van Wagner, C. E. and T. L. Pickett. 1985. Equations and FORTRAN program for the Canadian forest fire weather index system. Petawawa National Forestry Institute. Canadian Forestry Service. Forestry Technical report 33.

Van Wagner, C. E. 1990. Six decades of Forest Science in Canada. *The Forestry Chronicle*. 66(2):133-137.

Van Wilgen, B. W. 1984. Adaptation of the United States fire danger rating system to Fynbos conditions. South African Forestry Journal. Part 1. A fuel model for fire danger rating in the Fynbos biome. 129:61-65.

Weil, J. C. 1988. Atmospheric dispersion – observation and models. *In* Flow and Transport in the Natural Environment: Advances and Applications (W. L. Steffen and O. T. Denmead, ed.) Springer-Verlag, Berlin, Heidelberg. New York.

Werth P. and R. Ochoa. 1990. The Haines Index and Idaho Wildfire Growth. *Fire Management Notes.* 51(4): 9-13.

Werth J. and P. Werth. 1998. Haines Index Climatology for the western United States. *Fire Management Notes.* 58(3): 8-17.

Woodcock, J. 1993. A fire danger rating system for Israel. FAO/ECE/ILO International Forest Fire News. No. 8. http://www.uni-freiburg.de/fireglobe/iffn/country/il/il_1.htm

Wildland Fire Assessment System (WFAS). 2000. http://wfas.net/cgi-bin/nav.cgi?pages =wfas&mode=12.US Department of Agriculture. Forest Service.

Yang Yun-Qian and Jin Ji-Zhong. 1989. The climatic background and weather conditions of 1987 Daxinganling extreme forest fire in China. Pages 364-376 *in* Proceedings of the 10th Conference on Fire and Forest Meteorology, (D. C. Maciver, H. Auld, and R. Whitewood, ed.). Ottawa, Canada April 17-21, 1989.

Other Suggested Reading:

Alexander, M.E., E. B. D. Lawson, B. J. Stocks, and C. E. Van Wagner. 1984. User guide to the Canadian Forest Fire Behaviour Prediction System, Interm Edition, Canadian Forest Service, 76 p.

Deeming, J. E. 1995. Development of a Fire Danger Rating System for East Kalimantan, Indonesia. Integrated Forest Fire Management Document No. 2.

Cheney, N.P., Gould, J.S. and Catchpole, W.R. 1998. Prediction of fire behaviour in grasslands. *Int. J. Wildland Fire* **8**(1): 1-13.

Crane, W. J. B. 1982. Computing grassland and forest fire behavior, relative humidity and drought index by pocket calculator. *Australian Forestry.* 45(2):89-97.

Lavdas, L. G. 1996. Improving control of smoke from prescribed fire using low visibility occurrence risk index. *Southern Journal of Applied Forestry.* 20(1): 10-14.

L'vov, P. N. and A. I. Orlov. 1972. Determination of fire hazard in forests of Arkhangelsk Oblast. Lesnoye Khozyaystvo 6, 70-72 <In Russian>.

Nesterov, V. G. 1949. Combustibility of the forest and methods for its determination. USSR State Industry Press <in Russian>.

Scire, J., E. M. Insley, R. J. Yamartino, and M. E. Fernua. 1995. A users guide for CalMet meteorological model. Doc 1406. Concord, MA. Sigma Research/Earth Tech. 221 p.

Scire, J., D. G. Strimaitis, R. J. Yamartino, and Zhang Xiaomong. 1995. A users guide for CalPuff dispersion model. Doc 1321-2. Concord, MA. Sigma Research/Earth Tech. 315 p.

Snytkin. G. V. 1971. Determining forest fire danger in forests of the extreme northeast. Lesnoye Khozyaystvo 4, 67-69 <In Russian>.

Telitsyn, G. P. 1970. Logarithmic fire danger index. *Lesnoye Khozyaystvo*. 11: 6-10 <In Russian>.

Van Wagner, C. E., 1987. Development and structure of the Canadian Forest Weather Index System. Canadian Forest Service, For. Tech. Rep. 35. 37p.

CHAPTER 3

AGROMETEOROLOGICAL APPLICATIONS FOR SUSTAINABLE MANAGEMENT OF LIVESTOCK IN THE CENTRAL ASIA REGION

by Mrs. L. Grom
Meteorological Service of Uzbekistan

3.1 INTRODUCTION

An agrometeorological service is one that provides information on meteorological conditions, soil, plant, and other characteristics that affect agricultural production (Rijks, 1978). The aim of such services is to utilize the meteorological information on a real-time basis for various agricultural operations including irrigation scheduling. This also helps monitoring the stage and state of crops, the impact of prevailing weather on them and also the likely effect of forecasted weather on their future performance.

Agrometeorological services have great potentialities in effectively dealing with specific problems, especially while planning long term strategies, e.g. land utilization, introduction of new cultivars and in the design and utilization of farm irrigation systems, farm structures and machinery, etc. For all such purposes the identification of climate profiles suitable for the problems under consideration is a must. These services could also be of assistance help in short-term decision-making processes in the day-to-day management of farming operations, such as the deployment of labour, irrigation scheduling, application of fertilizers, etc. (Khambee, 1992).

Any development of irrigation management technique using soil, plant, and climate as inputs for enhancing agricultural production entails the acquisition of a reliable database on the quality of water, soil, and crop growth, together with the concomitant climatic features affecting irrigation requirements. An operationally effective agrometeorological service should therefore ensure the collection of required information from different sources and analyses of those data. Summarizing and interpretation of that analyzed information will be useful in formulating irrigation scheduling and can be disseminated through agromet advisory bulletins.

3.2 AGROMETEOROLOGICAL SERVICES AND IRRIGATION MANAGEMENT

Agricultural production in most countries is in the hands of subsistence farmers, employing traditional cultivation and irrigation techniques evolved from individual and social experience. Therefore, the need for enhancing the agricultural output has given rise to a new awareness to utilize all available resources, namely soil, climate and water.

Amongst all types of weather forecasts and special weather bulletins, agrometeorological advisory bulletins for the farming community seem to be the most important and give not only the weather forecast, information on crop stage and state but also advisories for time and mode of application of irrigation, fertilizers, pesticides, etc. Information on various types of advisories issued by different countries is summarized in Table 3. Out of 29 countries, 16 have said that special weather forecasts or advisories are issued in some form for irrigation scheduling. Most of the countries disseminate their advisories through radio/TV. In Israel, farmers are provided with such information by telephone and, in general, the agricultural community nowadays is aware of the importance of these advisories for their day-to-day irrigation scheduling. Thirteen countries have reported that they do not issue such agrometeorological information.

Table 3. Special weather forecast/advisory for irrigation scheduling

S.N.	Country	Weather forecast/ advisory for irrigation issued or not	Special weather forecast/advisory
1	India	Yes	Advice for irrigation is issued through agromet assessment bulletins/agromet field unit bulletins
2	Pakistan	Yes	Not in use in farmers fields
3	Philippines	No	
4	Sri Lanka	No	
5	Thailand	No	
6	Uzbekistan	Yes	The meteorological service issue 10-day agrometeorological and hydrological bulletins, as well as river flow forecast
7	Bulgaria	Yes	Monthly and weekly agrometeorological assessment and prediction
8	Egypt	Yes	Reported that scheduling irrigation could be done using the models, viz. CERES wheat, maize, rice, etc.
9	Sudan	Yes	Provide information on rainfall, wind, temperature, humidity and sunshine hours
10	Israel	Yes	Farmers are provided with information by telephone from the meteorological service and from local agrometeorological stations
11	The Netherlands	No	
12	Fiji	Yes	For the operation of irrigation system information on moisture status around root systems, tensiometer readings are used
13	UAE	Yes	Summary of climatological data is published on a regular basis for general use
14	Czech Republic	No	
15	Greece	No	
16	Jamaica	No	
17	Malaysia	No	
18	Slovak Republic	No	
19	I.R. of Iran	Yes	Water requirement is calculated based on weather data

S.N.	Country	Weather forecast/ advisory for irrigation issued or not	Special weather forecast/advisory
20	Kyrgyzstan	Yes	During the growing period, this is the most important work with regard to irrigation scheduling; data are published in weather bulletins, as well as 10-day and seasonal reviews
21	Romania	Yes	Details not provided
22	Switzerland	No	
23	Cameroon	Yes	Soil-water-atmosphere relationships are used for particular attention and accurate management (mainly in the Sahelian zone); otherwise there is a risk of soil structure degradation (compaction, crust, infiltration) and the washing away of chemical nutrients
24	Cap Vert	Yes	Weather forecast/advisory does not reach to countrymen
25	Chile	No	
26	Uruguay	No	
27	Saudi Arabia	No	Only max/min temperatures and weather forecasts are issued
28	South Africa	Yes	Information not provided
29	Austria	Yes	Information not provided

Information requirement for irrigation management in Humid areas

Irrigation in humid areas is very often economical even though annual rainfall may exceed annual ET. The feasibility of irrigation in humid areas will require that:

(i) the distribution of crop water demand throughout the growing season does not coincide with the distribution of rainfall; and
(ii) soil water storage within the root zone volume will not supply sufficient water to the crop during dry periods.

The purpose of irrigation in humid areas is to increase ET but with minimal losses by runoff, drainage, and the leaching of fertilizers and pesticides. The ideal situation would be the avoidance of water stress throughout the growing season and at the same time having no water loss. Scheduling under conditions of rainfall is thus the major goal of irrigation in humid areas. It is of importance to refill only part of the profile at each irrigation, leaving some storage to be filled by forthcoming rain, which can be calculated by using a long series of rainfall data.

One of the most common methods of irrigation scheduling is based on field soil water budget. Based on the effective rainfall or applied irrigation on the incoming side, ET on the depletion side and information on root depth, water storage capacity in the soil and the amount of available water at the beginning of the season and the allowable soil water depletion, water budgeting could be done on a weekly and a daily basis. A major problem in this regard is the determination of effective rainfall as incoming water. As this is the portion of rainfall that contributes to ET, rainwater lost by surface run-off or by sub-surface drainage has to be ignored.

Rainfall of high intensity or large amounts during a single storm may produce significant runoff and only part of the rainwater can be considered as effective. Similarly, rainfall on a wet soil profile will be ineffective, as most of the water will be lost by drainage. Rainfall when the crop is at an advanced stage of development and has a low transpiration rate is of low benefit, unless it is stored for the next crop. Very light rains may not contribute much to the storage as most of the water will be directly evaporated. A detailed and quantitative method to estimate effective rainfall from total measured rainfall was outlined by Dastane (1974), based on monthly ET and precipitation values. It indicates that effective rainfall as defined for irrigation purposes is also related to irrigation frequency.

Information requirement for irrigation management in arid lands

Irrigation water is the most important input limiting agricultural development in arid lands. This development is mostly achieved by importing water from other areas. This water has a very high economic value and many policy issues are involved in its use for agricultural development and for the overall economic growth of the region, such as the level of irrigation technology to be used and the cropping pattern and area to be committed for irrigation.

About 36% of the total land area of the world is arid. This area has been water-starved since time immemorial. However, current policies in water resource development have brought about a transformation in this area. Water for agriculture is now available, either in the form of precipitation, groundwater, or surface water imported from other drainage basins. Good water harvesting techniques, which are usually capital intensive, are needed in rain-fed agriculture. This helps to reduce the risk in dry land farming. The situation can be improved by developing better prediction methods of rainwater availability. The peak water availability period and critical growth stages when the water requirement is high could then be matched so as to maximize production. However, policies relating to this dry farming irrigation involve issues of decisions made under risk and uncertainty.

The fixed quantity of water available in a canal can be used to meet the full consumptive water requirements of the plants in a limited area, thereby getting the maximum crop yield per unit area. This could also be utilized for a greater cropped area with water use by the plants per unit area less than their consumptive requirements and with crop yields less than the maximum. This policy question was looked into by determining the benefits and agricultural employment opportunities for high agricultural technology for two cases: (i) the water supplied to the plants is 100% to their consumptive requirements, and (ii) the water supplied to the plants is only 60% of their consumptive requirements. The results indicate that when the water supplied to the plants was only 60% of their consumptive requirements, the total benefits of the Rajasthan Canal Project in India were reduced to about 40% while the cropped area of the project increased by about 50%. If the additional cost required in developing on-farm works for the increased cropped area are taken into account, the total benefits of the project with a water use of 60% of the consumptive requirements should be less than half the consumptive requirements of the plants satisfied from the canal water. Water use policies in arid lands should be based on the principle of maximizing benefits and/or agricultural production. High agricultural and irrigation technologies should be used to maximize benefits/production per unit of water and land area. Intensive agriculture at a high technology level will result in higher economic efficiency as well as opportunities for more agricultural employment (Verma, 1983).

Bettering the conditions of arid and desert environments is a matter not only of supplying adequate water, but of permanent maintenance of fertility and quality of soil water through efficient irrigation, drainage, soil reclamation and an optimally economic and sustainable land use pattern. The irrigation development programme in arid regions should focus on human use systems and on problems of land and water resource management with minimum environmental deterioration (Bithu, 1983).

3.3 AGROMETEOROLOGICAL APPLICATION FOR SUSTAINABLE MANAGEMENT OF LIVESTOCK

Pseudosteppe-pasture vegetation is characterized by a rare cover and relatively low productivity. Besides, by reason of unbalanced precipitation in various regions there are different moistening conditions, i.e. the basis for pasture vegetation formation. Year-to-year variations of the yield value are significant.

National hydrometeorological services of the Central Asian republics in the early 80's have done an extensive collaborative work on the development and the preparation of "Methodical instructions on compiling the maps of fodder reserves in desert and semidesert pastures in seasons on the basis of aerophotometry information".

Based on the "Methodical instructions…" introduced into operative practice of agrometeorological support, the following information on pasture types and regions was presented for the concerned organizations and agencies:

- total spring forage reserves,
- forage reserves eaten in a spring period,
- total summer forage reserves,
- forage reserves eaten in a summer period,
- forage reserves eaten in an autumn period,
- forage reserves eaten in a winter period.

In Uzbekistan the "Procedure of assessing forage reserves in desert and semidesert pastures from digital satellite information" was introduced in operative practice from 1996. The Central Asian desert and semidesert pastures are regions of intensive astrakhan sheep grazing, under the influence of which the fodder conditions have become worse and pasture degradation processes are intensified. A certain work has been performed for complex agro meteorological assessment of pasture conditions in the desert and semidesert Uzbekistan regions on the basis of standard meteorological data which favours the measures on grazing stock and pasture conservation. Complex assessment was performed from daily and decadal agrometeorological information, aerophotometry surveys, digital satellite data on the mean pasture vegetation harvest and forage reserves.

Complex assessment results allowed to isolate the agro-climatic peculiarities and tendencies in the pasture territory conditions, which served the basis for zonation and recommendations on the optimum pasture utilization. Agroclimatic zonation was performed in seasons. Based on the zonation performed, the regions were determined with the conditions favourable and unfavourable for the pasture vegetation formation.

Deterioration of the Aral Sea basin environment, associated with the Aral crisis, decreases the natural potential of pastures. Therefore the activities have been initiated on developing recommendations and proposals to improve the conditions of pasture vegetation formation and pasture cattle husbandry.

The increased pasture area productivity in Uzbekistan desert regions will be stipulated by:

a) autumn-summer and spring-summer sown pastures and haymaking in the foothills regions;

b) utilization of the local surface runoff from takyr and takyr-like soils by solonchak pastures;
c) increase of the fodder capacity of sandy desert pastures as the cost of highly productive fodder plants;
d) utilization of liman irrigation in the area of foothills, hills and mountains.

Water availability is a dominant factor for pasture on growth in arid and semi-arid regions. In its turn, livestock production directly depends on the availability of pasture. On the other hand, grazing animals can affect pasture growth in two different ways: grazing of animals has a positive effect if the number of grazing animals is well balanced with the capacity of the rangeland. But, overgrazing of rangelands by livestock is the main factor of degradation and desertification of grasslands. Therefore, pasture and livestock productions are closely related.

Vegetation in marginal regions is normally in ecological balance with the environment. It is usually when man's activities act together to upset this balance that desertification sets in. These activities come about as a result of an increased demand for food and lodging due to population rise. In dry regions, expansion of cultivated areas, overgrazing and deforestation expose the soil to wind and water erosion, thus producing or intensifying the process of desertification. Man's population started to increase rapidly in 1650 and this increase was highest in Asia and Africa, where the process of desertification is most intense.

In Asia, desertification occurs mostly in arid and semi-arid areas and caused mostly by frequent occurrence of drought, bad irrigation practices, deforestation, over-cropping, and overgrazing leading grasslands to recede.

This report focuses on weather and climatic aspects of pasture and livestock production in arid and semi-arid regions, especially in example of Mongolian Gobi desert area. For this purpose, information was obtained from studies made in Mongolia, China, Kazakstan, Russian Federation and others.

Agroclimatic conditions of the arid and semi-arid regions

Under arid conditions, there is no balance between rainfall and potential evapotranspiration; the rate of evaporation being more than the amount of precipitation. The simple definition given by Fuchs (1973) may be accepted: "When there is no season during which crops can be raised without irrigation, the climate is defined as arid". Mattel (1979) has utilized a similar definition in identifying the boundary between arid and semi-arid tropical areas. In quantitative terms, the arid zones can be agroclimatically defined as including those areas where:

The period with $r > 0.5$ PET is shorter than 60 consecutive days. The period with $r <$ PET is shorter than 60 consecutive days. The above characteristics refer to the months with mean minimum temperature above 10°C. In arid zones, therefore, agrosystems are only possible if supplemental water is available for crops. In the light of this assumption, it may be stated that, in these zones:

a) Agrosystems are not naturally in equilibrium with the environment.

b) Agrosystems need a complementary amount of water during almost all stages of the growing cycle. The quantity of water differs from one phenological phase to another.

c) Agrosystems take advantage of permanent high levels of radiation. Therefore, the potential productivity of the environment may be considered high when water is available.

d) The continuity of satisfactory yield levels of the agrosystems needs more attention in arid zones than elsewhere.

3.4 DROUGHT IMPACT ON PASTURE AND LIVESTOCK PRODUCTION IN ARID AND SEMI-ARID REGIONS

In Mongolia, drought is a negative factor in agriculture, food production, transportation and social field. Losses are important to national economy. According to statistics in an average year the yield losses are 14-15% of the total yield, livestock losses are 300,000-400,000 heads and direct losses are 18.5 million US$.

Drought impact consequence depends on local features, area affected and intensity. In addition to cattle, drought affects many other sectors of national economy, namely, agriculture. Year after year total surface suffering from drought shows a trend to increase due to climate change and also biological and anthropogenic factors. Droughts cause not only economic losses but also seriously affect the environment.

Description of drought in Mongolia

Drought is a natural phenomenon disturbing human activities for thousands of years. In hot Mongolian summers, drought often leads to loss of pasture and crop yield because of deficit in precipitation and soil moisture. It provokes feebleness and slimming of livestock in summer and autumn and deaths of a lot of pastoral livestock in winter and spring.

There are some cases of drought compiled for about 1,200 years. Scientific valid materials are saving up during latest 60 years in Mongolia. According to incomplete historical data, droughts affecting most of the territory in 1233, 1237, 1327, 1726, 1871, 1907, 1908, 1941, 1942, 1944, 1951, 1965, 1968, 1970 (Tsedevsuren, 1983).

In Mongolia, droughts are studied by Jambaajamts *et al,* (1973), Jadambaaa and Namhkai (1993), and Mijiddorj and Namhkai (1986), etc. Jadamba and Namhkai (1980) considered drought as an anomalous weather phenomenon have estimated it by means of a criterion expressing a combination of air temperature, humidity and precipitation anomaly. This considered, droughts happened over 50 days in Arhkangai, Uburhkangai, Gobi Altai, Selenge, Dornod aimags (provinces) and 40-45 days in the Gobi desert area. The maximum number of days with drought is about 100-200 per year. In other words some droughts continue for 3-4 months in the territory of Mongolia.

Drought-humidity index by Red (1975) has also been used to express the drought distribution and intensity as Si=AT/8T-AR/8R formulation developed by Mijiddorj and Namhkai (1986). By this study, drought occurs in all the territory twice, in 75% of the territory - 3 times, in 50% of the territory - 7 times, in 25% of the territory - 21 times in the last 45 years. In other words, drought has occurred once per 2-2.5 years in 25% of the territory and per 14-15 years in 75% of the territory. Drought spreaded in 25% of the territory usually has happened in the southern and western regions, correspondingly 75% in western and central regions.

Operative assessment of drought

Operative assessment and predictions of drought are of utmost significance in preparing early warnings to prevent or alleviate its impact and damage. Therefore present conditions of development of the country call for the creation and improvement of an integral system of drought monitoring, assessment and prediction. Multiple data sources have been used for monitoring vegetation, drought impacted areas and desertification. These sources include the following:

- satellite remote sensing
- ground measurement and agrometeorological station observations

Drought mitigation and management issues

At present, property forms in Mongolia have basically changed and property rights and its legal documents are renewed. Under new conditions, one has to change and improve methods of work for mitigation of drought impacts and damages. Mitigation activities are dependent on the intensities of drought, public and private intervention, disaster management experiences and economic capacity.

The most important drought mitigation activities that should be accomplished are the following:

In agriculture

- manage the irrigation system
- snow cover at winter time, it will melt and soak into the soil and protect soil from spring
- dryness
- cultivate plants non-sensitive to drought
- select plant area in deep soil with good water accumulation
- build windbreaks to reduce evapotranspiration
- define irrigation time, type, volume, interval, and intensity with consideration soil and vegetation specific and growing stages (slow irrigation in the morning when evapotranspiration is low)
- replace high consuming water plants by drought resistant species

In livestock

- move to places not affected by drought
- use modern technology to regulate herd size
- provide feed
- create local fodder supply
- supply additional water to animals eating dry food
- do not overgraze
- distribute livestock in adequate rate to poor grassland
- provide population drought warnings and assessments

In public works

- develop water supply and irrigation system
- use under ground water sources by digging wells

In environment

- improve drought evaluation
- reduce desertification by stopping sandy dunes displacement

- estimate land carrying capacity appropriate to climate condition and plant resources to avoid overgrazing
- estimate livestock carrying capacity on the basis of existing grassland capacity
- not to increase unit area density in areas vulnerable to drought

3.5 EXAMPLES OF EXPECTED EFFECTS OF CLIMATE CHANGE

First studies of the Central Asia climate change and variability have been performed by Uzbekistan Glavhydromet. To assess the changes in agroclimatic resources and their impact on agricultural production, the regional climate scenarios showing climate change values by 2030 were taken as the base scenarios of climate change. Background scenario values were brought into line with the real climate differentiation of Uzbekistan territory and referred to agroclimatic districts and regions. Variations in the mean seasonal temperature for agroclimatic districts and regions were determined up to 2015-2030. A general trend and cyclic variations in the primary characteristics of agroclimatic resources were noted. Diversity of agroclimatic conditions in the republic, their year-to-year variability and expected air temperature rise as a result of expected climate change require the comprehensive consideration of the possible impact on crop productivity.

To this end, the first proposals are presented on the expected impact of agrometeorological application stimulating the increase in cotton-growing productivity and sustainability. Expected changes of agroclimatic resources in primary cotton-growing regions will result in an increased vegetation period duration, and increased summer and autumn temperatures. As a result, the conditions of cotton boll formation, opening and maturation will be better and result in an increase of the raw-cotton yield and its quality improvement.

Warming will have a positive effect in the northern regions, hence, a vegetation period will be longer. Increase in the extremely high air temperatures will result in crop yield depression in some regions. Under low moisture supply conditions the crop yield loss at the cost of "ballast" temperatures may amount to 9-15% on the average. Under optimum water supply conditions an 11% increase in the cotton yield is expected practically in all Uzbekistan regions. The cotton yield in Uzbekistan as a whole will grow relative to the mean value (1960-1996), but not exceed the maximum crop yield of the 1980's in the 20th century.

3.6 REFERENCES

Abdullaev A.Kh. 1997. Agrometeorological assessment of the cotton state and its crop yield forecast in Uzbekistan. Tashkent: SANIGMI, 173pp.

Aryshanov M.L., M.V. Sitnikova, and T.E. Sumochkina. 1999. Assessment of soil-plant object conditions from NOAA-AVHRR data // Proc. USOI . Vyp.1 p.117-130.

Babushkin O.L. and T.E. Sumochkina. 1998. Climate impact on agroclimatic conditions of pasture plant growing. // Proc. SANIGMI. Vyp. 158(239). - p.113-118 hanwar, Dan Bithu, 1983. Environmental impact of irrigation in arid area. Proceedings of the seminar on irrigation in arid lands, 1:77-84.

Chub V.E. 2000. Climate change and its effect on the natural- climatic potential of Uzbekistan. Tashkent: Glavhydromet, 249pp.

Dagvadorj D. 2000. Weather and climate related to pasture and livestock production in arid and semi-arid regions. CagM Report No.79, WMO/TD No.989, Geneva, Switzerland.

Dastane, N.G. 1974.Effective rainfall. FAO irrigation and drainage 1, Pap.17:1-61.

Fuchs, M. 1973. The estimations of evapotranspiratin. In arid zone irrigation. Ecological studies, 5, Springer Verlag, p. 241-247.

Jambaajamts, B. And B. Jambaagarav. 1973. Drought and its Freguency. Issues of Geography of Mongolia, Ulaanbaatar, Mongolia, 12:45-65 (in Mongolian).

Jadambaa Sh. and A. Namhkai. 1980. On Drought Study, Papers of IMH, Ulaanbaatar, Mongolia, 5:15-32 (in Mongolian).

Khambee, N.N. 1992. Development of Agrometeorological Services in Developing Countries. CAgM Report No. 44. WMO/TD No. 501, 75 pp.

Mijiddori, R. and A. Hamhkai. 1986. On Drought and Unfavorable Winter Weather Conditions Recurrence on the MPR’s territory. Papers of IMH, Mongolia, 11:118-131 (in Russian).

Mattei, F. 1979. Climatic variability and agriculture in the semi-arid tropics. Proceedings of the World Climate Conference. WMO No.537, WMO, Geneva, Switzerland.

Namkhai, A. 1993. Freguency of extreme phenomena (drought and severe winter) occurrences in the Central Asia. Proceedings of the First Mongolia-China Workshop on Climate Change in Arid and Semi-arid regions over the Central Asia, 8-11 May 1993, Beijing, China, p. 60-68.

Ped, D.A. 1975. On Parameters of Drought and Humidity, Papers of HMC, SSSR, 156:19-38.

Rijks, D. 1978. Agrometeorological network over Africa. Proceedings Agrometeorological Research Needs of the Semi-Arid Tropics, ICRISAT, Patancheru, AP, India.

Samui R.R., and A.K. Abdullaev. 2000. Validation of information reguirements on irrigated soils and crops CagM Report No.80, WMO/TD No.997, Geneva, Switzerland.

Tsedevsuren D. 1983. On the issue of the application of drought and extremely severe winter occurrences over the Central and Eastern regions of Mongolia. Papers of HMRI, No.8, p.93-00.

Verma, R.D. 1983. Water use policy for irrigation in arid lands. Proceedings of the seminar on irrigation in arid lands, 1:5-9.

CHAPTER 4

IMPACTS OF AGROMETEOROLOGICAL APPLICATIONS FOR SUSTAINABLE MANAGEMENT OF FARMING SYSTEMS, FORESTRY AND LIVESTOCK IN SUB-SAHARAN AFRICA

by Mamadou Ndiaye
National Meteorological Service of Senegal

4.1 INTRODUCTION

Agriculture plays a major role in Africa, occupying more than half of the active population. Being still of the traditional type, agriculture faces enormous problems, the most frequent being:

- Soil exhaustion (particularly in the Sahel) usually due to insufficient (or no) fertilization and insufficient fallow periods;

- Lack of irrigation, causing considerable dependency on climatic conditions. In most countries agriculture produces barely enough to feed the population in the years of good rainfall; as soon as a shortage of rainfall is observed (as is often the case in the Sahel belt or in Eastern Africa), production drops spectacularly, often leading to famine or mass migration to the towns;

- A very low level of mechanization, since the peasant farmers still work with fairly basic tools, causing performance to be very low.

In addition to these technical and material limitations, much of the African continent (particularly the Sahel belt) has been experiencing severe drought for several years shortening the growing season.

In spite of all these constraints and owing to a lack of valid alternatives, farming is the only means of subsistence available for the majority of the population. This system of farming would greatly benefit from agrometeorological inputs with appropriate advice, particularly as regards selecting crop varieties, planning the crop calendar and knowing the best moments to carry out certain operations so as to minimize climate-induced risks. Rural assistance programmes which apply agrometeorological knowledge were started several years ago in the Sahel countries, but most of the African continent has not seen such programmes.

4.2 APPLICATION OF AGROMETEOROLOGY FOR THE SUSTAINABLE DEVELOPMENT OF AGRICULTURE IN BLACK AFRICA SERVICES RESPONSIBLE FOR THE IMPACT OF AGROMETEOROLOGY ON AGRICULTURE

Surveys in the different African countries show that the national Meteorological Services are the main actors applying meteorology to agriculture. They also show that there are not very many associations which ensure the connection between the producers and the users of agrometeorological products, with the exception of a few countries in which some agricultural research centres also cater to this aspect.

There is a programme, AGRHYMET (agrohydrometeorology), for the Sahel countries which are members of the Permanent Inter-State Committee on Drought Control in the Sahel (CILSS) for developing agrometeorological applications to mitigate the effects of drought (which has raged since the beginning of the 1970s) on agriculture.

Access to agrometeorological information

In almost all countries, agrometeorological information is made available to the users free of charge. Although this policy does not generate income for the Meteorological Services, it enables the national users who do not have considerable financial means (over 70% of all users) to have access to information which is important for their activities. There is, however, a few countries in which meteorological services are commercialized, some having single tariffs which are well adapted to the clients' means.

The users are becoming more interested in agrometeorological forecasts, which constitute 43% of the requirements. Agrometeorological advice is also widely requested and represents almost 40% of demand.

Tools for developing the different agrometeorological products

Computers with appropriate software are predominantly used to develop the different agrometeorological products. The INSTAT statistical software developed by the University of Reading (UK) is the most widely used. This software, which enables very different products to be developed (simple statistics, water balance, etc), has benefited from a WMO training programme throughout all the African countries where it is very widely used. Satellite imagery is also very widely used to develop products such as the Normalized Difference Vegetation index (NDVI). Lesser-known software, such as that developed by the AGRHYMET centre in cooperation with FAO and WMO are also used.

The advantages of meteorology

Although many countries have not assessed the agricultural advantages of agrometeorology, it can, however, be noted that agrometeorology generates income for agriculture, even if the actual percentage figure is unknown. Other countries estimate that this income is 30-40 %.

On the other hand, it can be seen that agrometeorological information contributes considerably to reducing losses caused by severe weather conditions such as drought, which is a regular occurrence in many African countries. Some countries estimate that these losses are reduced by between 30 and 50 %. In agriculture, it is the loss of seed due to irregular rainfall at the start of the season that is signalled.

AGRHYMET supports all Sahel countries giving agrometeorological advice in order to reduce drought-associated losses (loss of seed, fertilizer, working time, etc.).

Assessing the impact of agrometeorological applications

Most African countries have not assessed the agricultural efficiency of agrometeorological information. However, different field trips have enabled some countries to report.

In Senegal and Mali, socio-economic assessments of agrometeorological projects to assist agriculture were carried out by teams of several specialists. These showed that the information given to the farmers caused them to act differently, considering the agrometeorological advice given by the assistance teams before working in the fields.

4.3 EXAMPLES OF AGROMETEOROLOGICAL APPLICATIONS

Agroclimatic reference calendar

With the northward migration of the inter-tropical front, winter sets in progressively in the different regions it crosses. Rain at the beginning of the season is unfortunately, irregular, and this can sometimes cause loss of seed and necessitate re-sowing.

In Mali, the Meteorological Services have promoted an agroclimatic reference calendar among farmers. This calendar fixes the minimum rainfall required before sowing for each period (at the beginning of the wet season). This application, although very simple, helps to avoid considerable loss of seed and working time in areas in which farmers' income is very low.

Relay crops

A season in the Sahel lasts three months on average. The rural population take all their food and income from farming during this brief period. The length of season only allows one crop per year.

Research carried out at the ICRISAT Sahel Centre, Niamey (Niger) by Dr. Sivakumar has enabled a relationship between length of wet season and the date of the first useful rain to be established. It shows that the season is as much longer as the first rain is early.

In this application, when winter is fairly early, a second crop is attempted. In the years in which rain comes often after harvest, the relay crop (china beans or feed-grade groundnuts) sown between lines could also benefit from the soil reserves which run out approximately 20 days after the last rain. This crop could thus develop sufficiently to produce quality forage and generate a certain amount of income for farmers.

4.4 USE OF THE GEOGRAPHICAL INFORMATION SYSTEM

The Geographical Information System (GIS) software is very useful for agrometeorology and enables many products to be developed by combining several layers of information. Unfortunately the GIS is very rarely used by the African Meteorological Services. Nevertheless, a select few Meteorological Services use these products. On the whole, these Services have all already carried out an ecological zoning of their country. In the future, the World Meteorological Organization should help promote this software via training workshops similar to those given for CLICOM.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

by Prof. A. Kleschenko,
National Institute on Agricultural Meteorology
Hydrometeorological Service of Russia
E-mail: cxm@meteo.ru

5.1 CONCLUSIONS

The steady increase in human populations and periodic natural hazards, such as drought, flood, frost etc., have caused food shortages, stressed resources along with increased chemical and technogenic loads, and have jeopardized the long-term sustainably of these agricultural systems. In the light of expected climate change in some regions, it should be noted that a system becomes unsustainable when the cost of protection far exceeds the ability of the national economy to cope with it (Sivakumar et al, 2000).

Development of sustainable food production strategies requires a deeper understanding of the limitations of the ecosystem and of the interrelationships between crops, trees, and livestock and determining the impact of sustained use of a given production system on the resource base.

Climate is one of the most important factors determining the sustainability of agricultural production systems and more emphasis should be placed on understanding its potential and limitations.

Speaking about agrometeorological applications for sustainable management of farming systems, forestry and livestock, it should be remembered that any management decision, in addition to increase in sustainability, should allow profit-making from these applications.

To increase the efficiency of agrometeorological applications, more emphasis should be placed on multidisciplinary research that brings together agroclimatologists, agronomists, soil scientists, agroforesters, and livestock specialists. Three International Conventions (Sivakumar et al, 2000) and the World Food Summit Plan of Action have highlighted the priorities for agrometeorological applications the solution of which will play a pro-active role in promoting sustainable development in the 21st century.

5.2 RECOMMENDATIONS

1. Assessment of the impact of agrometeorological applications for sustainable management of farming systems, forestry, and livestock is one of the most important problems of agrometeorology in our century.
2. Despite many different agrometeorological and agroclimatic applications, there is a small number of examples of their impact on decision-making for management of farming systems, forestry, and livestock with the account of ecological safety and sustainable development.
3. In the development of different agrometeorological applications for farming systems, forestry, and livestock it is necessary to consider not only the effect of these applications, but also their impact on the sustainability of applied systems.
4. An important goal in agrometeorology should be developing mathematical models which consider the problems of sustainability and anthropogenic effects of fertilizers, pesticides and other chemicals on agricultural products.

5. In the wide-ranging forestry field, there are several areas in which agrometeorological applications can be used, including: fire behaviour/danger, fire management, prescribed burning and fire effects, climate change, smoke management and air quality, and forest health and productivity.
6. A more wider use of geographical information systems, remote sensing applications, and agroecological zoning is important for sustainable management of farming systems, forestry, and livestock.
7. Considering the great importance of agrometeorological applications for sustainable management of farming systems, forestry, and livestock it is desirable to continue data storage and analysis on this problem in the framework of CAgM activities between the XIII and XIV Sessions.