

## Agrometeorology and sustainable agriculture

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### Abstract

Current concerns with the sustainability of agroecosystems in different parts of the world have heightened the awareness for careful use of the natural resource base on which agriculture depends. For proper and efficient use of soils and plant/animal genetic material, knowledge of the role of climate is an essential precondition. Several elements of the chapters in Agenda 21, a global plan of action agreed at the United Nations Conference on Environment and Development (UNCED), require the attention of the agrometeorologists and these have been reviewed. Three International Conventions which have a bearing on sustainable agriculture including the United Nations Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity (CBD) and the United Nations Convention to Combat Desertification (UNCCD) were negotiated and ratified since 1992. The World Food Summit Plan of Action (WFSPA), which was developed in 1996, includes several commitments to make agricultural production sustainable. Agrometeorological aspects of these three Conventions and the WFSPA were reviewed. Some of the priorities for agrometeorologists to address sustainable agriculture in the 21st Century were discussed. These include 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 and promotion of geographical information systems and remote sensing applications and agroecological zoning for sustainable management of farming systems, forestry and livestock. Other priorities include 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 and promoting a better understanding of the interactions between climate and biological diversity. These present important challenges and great opportunities for agrometeorologists to play a proactive role in promoting sustainable development in the 21st Century. © 2000 Elsevier Science B.V. All rights reserved.

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### 1. Introduction

The recent emphasis on sustainability in several world forums makes one wonder whether it is a philosophy, a long term goal or a set of management practices (Francis et al., 1988). It is however incontestable that sustainable agriculture is seen as an important goal throughout the world. Rapidly rising population

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growth and diminishing arable land, particularly in the developing countries, has increased the stress on the natural resource base. Lal (1991) calculates that the per capita arable land will progressively decline from about 0.3 ha in 1990 to 0.23 ha by the year 2000, 0.15 ha by 2050 and 0.14 ha by 2100. Combined with the growing concerns regarding the decline in the non-renewable sources of energy and the degradation of environment, it is certainly timely that the world is taking a hard look at the way natural resources have been exploited so far with the sole objective of profitability rather than long term sustainability.

There is no generally accepted definition of sustainable agriculture (CGIAR/TAC, 1988). However, as Swindale (1988) explained, sustainability conveys the

idea of a balance between human needs and environmental concerns. A common theme among definitions is that sustainable agricultural systems remain productive over time (Senanayake, 1991). They should provide for the needs of current, as well as future generations, while conserving natural resources (NRC, 1991). The enhancement of the environmental quality and careful use of the resource base on which agriculture depends is viewed as a requisite to sustained agricultural productivity (ASA, 1989). In fact, a selection of the definitions of sustainability/sustainable systems from the literature (Table 1) shows that natural resource use is a keyword in almost all of them.

Basically, sustainable agriculture is a philosophy based on human goals and on understanding the long

Table 1  
Reference to the relevance of agroclimatic information in selected definitions of sustainability

Author	Definition of sustainability/ sustainable system(s)	Keywords for agroclimatic information
American Society of Agronomy (ASA, 1989)	That, over the long-term, enhances environmental quality and the resource base on which agriculture depends; provides for basic human food and fibre needs; is economically viable; and enhances the quality of life for farmers and society.	Environmental quality; resource base
Bifad (1988)	The successful management of resources for agriculture to satisfy changing human needs, while maintaining or enhancing the natural resource base and avoiding environmental degradation. One that should conserve and protect natural resources and allow for long term economic growth by managing all exploited resources for sustainable yields.	Management of resources; natural resource base; environmental degradation Natural resources; exploited resources
CGIAR/TAC (1988)	Sustainability refers to successful management of resources for agriculture to satisfy changing human needs while maintaining or enhancing the quality of the environment and conserving natural resources.	Quality of environment; natural resource conservation
Conway (1985)	Ability of a system to maintain productivity in spite of major disturbance such as is caused by intense or large perturbation.	Productivity (resources)
Davis and Schirmer (1987)	Among the topics considered under sustainable agriculture are resource management issues dealing with soils, land, natural resources and watersheds; and environmental problems such as desertification, soil degradation etc.	Natural resources; environmental problems
Dover and Talbot (1987)	Those systems whose production can continue indefinitely without undue degradation of other ecosystems.	Ecosystem degradation

Table 1 (Continued)

Author	Definition of sustainability/ sustainable system(s)	Keywords for agroclimatic information
Knezek et al. (1988)	Resource conserving and uses external and internal resources as efficiently as possible. Environmentally sound, actually enhancing rather than detracting from the natural environment. Economically viable in that it earns a fair return on farm investments.	Resource conserving; environmentally sound
Lal (1991)	An increasing trend in production over time per unit consumption of the non-renewable or the limiting resource, or per unit degradation of soil and environmental characteristics.	Resource use environmental characteristics.
Lynam and Herdt (1988)	The capacity of a system to maintain output at a level approximately equal to or greater than its historical average with the approximation determined by its historical variability.	(resources for) maintaining output
Okigbo (1991)	A system which maintains an acceptable and increasing level of productivity that satisfies prevailing needs and is continuously adapted to meet the future needs for increasing the carrying capacity of the resource base and other worth-while human needs. A system in which the farmer continuously increases productivity at levels that are economically viable, ecologically sound, and culturally acceptable, through the efficient management of resources and orchestration of inputs in numbers, quantities, sequences and timing with minimum damage to the environment and danger to human life.	Resource base Ecologically sound; management of resources
Rodale (1988)	The system where the resources used in production are maintained in such a way that they are more or less self-generating and ensure continual improvement beyond conventional expectations.	Self-generating; production resources
Rome Forum (1986)	Efforts to achieve sustainable food security should blend the unique features that cater for specific cultural economic and ecological conditions among countries and within different regions in the same country.	Ecological conditions
Ruttan (1989)	Development of technology and practices that maintain and/or enhance the quality of land and water resources. The improvement in plants and animals and the advances in production practices that will facilitate the substitution of biological technology for chemical technology.	Land and water resources
WCED (1987)	Conserving and enhancing the resource base and merging economics and environment in decision making are among the objectives for sustainable development.	Resource base; environment

term impact of our activities on the environment and other species (Francis, 1990). Broad concepts in sustainable agriculture encompass ecological, economic, and social parameters, whereas more narrowly defined concepts are mostly concerned with environmental issues such as optimal resource and environmental management (McCracken and Pretty, 1990).

The notion that sustainable agricultural systems ‘maintain output in spite of major disturbance, such as caused by intensive stress or large perturbation’ (Conway, 1985) is of particular relevance to semi-arid ecosystems. The high rainfall variability of the semi-arid zone can cause wide fluctuations in agricultural productivity and has profound impacts on the ecology, economy and social welfare of the people of the region. Even the more productive river deltas, although not specifically fragile, are the result of a long evolution and are, in the words of Riebsame et al. (1995), tuned to the current climate. Any departure from the current equilibrium, even one that would a priori be positive (e.g. better rainfall/evaporation ratio), results in a temporary disturbance of the ecology and productivity.

## 2. Importance of agroclimatic considerations in sustainable agriculture

There is a lot to be gained from looking at climate not only as a hazard, but also as a ‘resource’. Resources must be known, assessed in quantitative terms and properly managed if they are to be used sustainably, and climate is no exception (Gommes and Fresco, 1998).

Amongst the natural resources i.e. climate, soil, and plant/animal genetic material, that are essential for agricultural production, from the standpoint of exploitation of available material, climate received far less attention in sustainable agriculture literature. Knowledge gathered about any of the inputs is proportional to the cost of supply of the inputs. Rijks (1991) argued that climate does not have a cost of development, supply or replacement in comparison to other inputs and hence received far less attention. In a literature search of the Agricola database using the keywords, ‘sustainable agriculture’ and ‘environment’, Baier (1990) found that none of the 85 records selected dealt specifically with climate! A

clear majority of them dealt with policies. A search of the global activities of the Commission for Agricultural Meteorology of WMO also did not reveal any direct reference to sustainable agriculture.

To stress the direct link between agricultural production potential and climate, Bernard (1992) uses the concept of climate fertility, coined after soil fertility. The fundamental similarities between climate and soil resources include the following: both contribute to the general production potential of a region, both undergo spatial variations and they can be mapped at different scales (Gommes and Fresco, 1998). In both cases their deficiencies can sometimes be corrected by adequate management practices. In addition, climate and soil contribute to agricultural production potential in an integrated way, not as separate factors, particularly since soil genesis is also very climate dependent.

Climate is a renewable resource, but is variable in time and space. For proper and efficient use of the other two natural resources (soil and plant/animal genetic material), knowledge of the role of climate is an essential precondition. In fact, climate should be regarded as the driving variable for exploitation of plant, animal and soil resources. Even the highest yielding, the most pest- and disease- resistant and fertilizer responsive seed can do little good to the farmer if it can not germinate when it is sown in soil. This is because biological entities, such as crops, are not abstract entities, but a product of their temporal and genetic history in varying environments (Senanayake, 1991) and there are lethal environmental thresholds which an organism cannot transcend. Many of the ecological implications of agricultural development require an improved understanding of interactions between the physical, biological and climatic components. As Thomas (1988) explained, the relationships between the productive capacity of the resource base and the adsorptive capacity of the environment — the increasing problems of water and air pollution, soil erosion, and potential changes in the micro- and macro-climate — are not well understood.

Climate is often the most critical factor determining the sustainability of agricultural systems and it constitutes a ‘complex’, i.e. consists of a set of variables which behave coherently, essentially as a result of atmospheric physics and dynamics (Sombroek and Gommes, 1996). For instance, rainfall tends to cool the atmosphere because water evaporation absorbs

heat; cloudy days are characterised by a low daily thermal amplitude (difference between day and night temperature), relatively high air moisture and low evaporation, etc. In addition, the statistical properties of climate derived from long-term observations ensure that the usual range of variation of the ‘complex’ is known. Notwithstanding the difficulties of short-term weather forecasts proper, weather thus behaves rather coherently, and this constitutes an essential piece of knowledge which can be applied to improve the output of agricultural systems in terms of amounts and regularity.

Stewart et al. (1989) presented an interesting picture of the difficulty of achieving sustainability of an agricultural system because of varying temperature and moisture regimes. As temperatures increase and amounts of rainfall decrease, the development of sustainable cropping systems becomes more difficult. Soil degradative processes such as organic matter decline and soil erosion are generally accelerated as temperatures increase. The potential for wind erosion also increases in warmer areas. A change in the moisture regimes towards more aridity also accelerates these degradative processes.

For agroclimatologists around the world, the new awareness of sustainability among their colleagues has opened up new and exciting opportunities for interaction as never before. The earlier concerns with profitability as the main goal kept the scientists and managers involved with agricultural research and development organizations more preoccupied with issues such as fertilizer use, water management, pest and disease control. There was little scope for interaction with the agroclimatologists except for occasional demands for weather data. The new concern with sustainability has drawn their attention towards the need for a greater understanding of the various aspects of natural resources including the nature of inherent variability, methods of efficient use while ensuring proper conservation, and the development of suitable practices to ensure resource amelioration in the long term. For example, while solar energy sets the maximum value of the energy available for plant growth, water determines to what extent the energy can be used. In fact, plants ‘pay’ for the energy they absorb by transpiring water, and similarly water plays an important part in the thermoregulation of animals. In other words, the energy balance and the water

balance of crops are interrelated through crop evapotranspiration (Gommes and Fresco, 1998). Climate resources also directly affect biodiversity of land and marine ecosystems (Laserra, 1992; MacDonald, 1992; Solbrig, 1992, and several chapters in Solbrig et al., 1992; WCMC, 1992; Tilman et al., 1997).

This increased awareness of the need for sustainability perspective has also led to changes in the research programs. For example, many of the traditional agronomy teaching and research programs are now giving way to the ‘Natural Resource Management Programs (NRMP)’, with increased emphasis on resource characterization and applications. The objective of NRMP is to develop systems of production which match improved genetic material from the crop breeding programs to the physical and social environments of the farming regions to which this material should be adapted. In this context, ‘matching’ means attempting to maximize production without sacrificing stability of yield from year to year and without squandering irreplaceable resources such as top soil and groundwater reserves. Thus, the role of the agroclimatologist in such changed research structures is now better recognized and is more sharply focussed.

### **3. Agenda 21, agrometeorology and sustainable agriculture**

The United Nations Conference on Environment and Development (UNCED) which took place in Rio de Janeiro, Brazil in June 1992 was an unprecedented event as significant topics of vital importance to the peoples of the world, particularly in relation to sustainable development, were addressed at the highest level. The Conference made it clear that we can no longer think of environment and economic and social development as isolated fields. The centerpiece of UNCED is the Agenda 21, a global plan of action which resulted from the consensus among all the countries and aims at reconciling the twin requirements of a high quality environment and a healthy economy for all peoples of the world. A 700 page document, structured into 40 chapters, is a dynamic programme of specific objectives and Agenda 21 actions for a ‘new global partnership for sustainable development’. Agenda 21 explains that population, consumption and technol-

ogy are the primary driving forces of environmental change and offers policies and programmes to achieve a sustainable balance between consumption, population and Earth's life-supporting capacity. It describes some of the technologies and techniques that need to be developed to provide for human needs while carefully managing natural resources.

A number of Chapters in Agenda 21 are of specific interest to Agrometeorology. These include, among others, the programme areas in Chapter 9 (Protection of the Atmosphere), Chapter 12 (Managing Fragile Ecosystems: Combating Desertification and Drought), Chapter 13 (Sustainable Mountain Development), Chapter 14 (Sustainable Agriculture and Rural Development), Chapter 18 (Protection of the Quality and Supply of Freshwater Resources), Chapter 35 (Science for Sustainable Development) and Chapter 36 (Education, Training and Public Awareness). Specific elements of these Chapters that call for the attention of the agrometeorologists include the following:

1. Research into an improved understanding natural climate variability and anthropogenic climate change, including biospheric processes influencing climate.
2. Enhancing the protection, sustainable management and conservation of all forests, and the greening of degraded areas, through forest rehabilitation, afforestation, reforestation and other rehabilitative means.
3. Strengthening the knowledge base and developing information and monitoring systems for regions prone to desertification and drought, including the economic and social aspects of these ecosystems. 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.
4. Developing comprehensive drought preparedness and drought-relief schemes, including self-help arrangements, for drought-prone areas. Research into seasonal forecasting and the strengthening of drought early warning systems and integrated packages at the farm and watershed level such as alternative cropping strategies, soil and water conservation and promotion of water harvesting techniques are stressed.
5. Identification of hazard-prone areas that are most vulnerable to erosion, floods, landslides, earthquakes, snow avalanches and other natural hazards and development of early warning systems and disaster-response teams.
6. Surveys and research to establish baseline information on the status of natural resources and to develop methodologies and tools of analysis such as environmental accounting, development of early warning systems to monitor food supply and demand, integrated pest management and control, sustainable plant nutrition to increase food production and research into the effect of increased ultraviolet radiation on plant and animal life as well as on sustainable agricultural development.
7. Conservation of biological diversity.
8. Protection of the quality and supply of freshwater resources: application of integrated approaches to the development, management and use of water resources.
9. Emphasis on the kind of science that can provide a clearer picture of how the environment works, and give better estimates of the Earth's capacity to deal with increasing human demands.
10. Promoting education, public awareness and training.

#### **4. Agrometeorological aspects in the International Conventions and World food Summit Plan of Action**

In a short span of 6 years since 1992, the world community has negotiated and ratified three important International Conventions, all of which have a significant bearing on sustainable agriculture. These include: the United Nations Framework Convention on Climate Change (UNFCCC); the Convention on Biological Diversity (CBD); and the United Nations Convention to Combat Desertification (UNCCD).

In addition to the above, the World Food Summit Plan of Action (WFSPA), which was developed in 1996, includes several commitments to make agricultural production sustainable.

Brief highlights of each of the three Conventions and the WFSPA are presented further. It is important to stress that although each of these Conventions addresses a major environmental issue, they all recog-

nize clearly the links with other Conventions in their respective preamble statements.

#### 4.1. *United Nations Framework Convention on Climate Change (UNFCCC)*

The UNFCCC came into force on 21 March 1994, 90 days after the date of deposit of the 50th instrument of ratification. The preamble of the UNFCCC highlights several points which are at the heart of the problem normally dealt with by international organisations, in particular the need for an international response. This applies particularly in the field of climate where, due to the very nature of the atmosphere, all physical causes and effects tend to be global in nature. This can be seen as one of the differences between the UNFCCC and other Conventions where causes and effects tend to be more local. We stress the word physical because other aspects (legal, methodological) tend to be more similar between all the recent international agreements with an environmental basis (convention on desertification, biodiversity).

Two additional points stressed in the preamble are particularly relevant to the agricultural community:

- The access to resources to achieve sustainable development, and
- The recognition of the basic differences between developing and developed country parties.

Regarding the first point, it should be underlined that the UNFCCC has relatively little direct reference to agriculture, i.e. sustainable development is mostly implicitly seen as sustainable economic growth (the Kyoto protocol, discussed in the next section, refers much more explicitly to the role and importance of agriculture in the broad sense). Agriculture is, however, mentioned in Article 2, which states that the ‘ultimate objective of this convention (...) is to achieve (...) stabilization of greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.’

Note the reference to the pace of change which has to be slowed down to allow ecosystems to reach new equilibrium states ‘naturally’. Agriculture has

the potential to adapt much faster in all those sectors where the management component plays a major part, i.e. essentially for field crops, livestock rearing, inland fisheries and some forms of marine plant and animal production. Adaptation may be more difficult in sectors such as grazing in natural pastures, or ocean fisheries where man basically only controls (manages) harvests in largely ‘natural’ ecosystems where the production side is still largely unmanaged. Forestry can occupy almost any position in the spectrum from controlled production and harvest to controlled harvest only, depending of the type and level of development and national forestry policies.

The last section of Article 2 again focuses on economic development but Article 3.4 (on Principles) underlines that policies to protect the climate system should be integrated with national development programmes, which necessarily includes agriculture. Similarly, Article 3.3, still without mentioning agriculture, underlines that all sources and sinks have to be taken into consideration.

The second point (differences between developed and developing countries), is stressed again in the section on the Commitments of the different Parties, where agriculture is repeatedly mentioned among the sources and potential sinks of greenhouse gases. The discussion on Research and Systematic Observation highlights the following aspects:

- The base of data available is often significantly poorer in developing countries than in the developed ones, and better data will probably only become available as a by-product of development;
- Because agriculture is still often at a subsistence level (we define subsistence farming as a type of agriculture where the farmers mostly grow their own food, usually under very low technology and high environmental risk, and little access to markets, if any), governments pay relatively little attention to agriculture in comparison to, say, energy imports and consumption, or to agriculture from the stage when it earns foreign exchange;
- It is not just crop and forestry statistics that are relevant to UNFCCC, as ruminant cattle and rice paddies are seen as a major source of methane, and fertiliser constitutes a source of nitrous oxides;
- There appears to be much less methodological standardisation in the area of agricultural observations than in the industrial and transport sectors, because

of the very differences between biology-based activities and industrial processes. As a result, the proper assessment of sources and sinks, as well as the assessment of impacts and adaptation potential are accordingly more difficult, and needy of technical assistance;

- Due to population pressure and urbanisation, many farmers in developing countries are currently forced out of their traditional subsistence systems into a more productive and market-oriented type of farming. Needless to say, this constitutes a very vulnerable situation due to the use of new crops and techniques, the exposure to market forces and probably to a changing global and local environment.

#### 4.1.1. *KYOTO Protocol*

The 3rd Conference of the Parties of the UNFCCC which took place in Kyoto during late 1997 led to the Kyoto Protocol which was open for signature at the UN Headquarters in New York until March 1999.

Compared with the UNFCCC, the Kyoto Protocol focuses much more explicitly on agriculture and forestry, in particular on sustainable forest management practices and on the promotion of sustainable forms of agriculture in the light of climate change considerations. It is interesting to note the wording ‘in the light of climate change considerations’ which stresses also climate extremes and variability and not just the sources of unsustainable agricultural practices.

The Kyoto protocol commits the signatories to reduce overall emissions of greenhouse gases by 5% below 1990 levels in the 5-year ‘commitment period’ from 2008 to 2012. In its Annex A, it also enters into significantly more detail than the UNFCCC regarding the gases which will be the object of the reduction: in addition to carbon dioxide, nitrous oxides and methane are mentioned, of which the latter largely stems from agriculture-related sources. More specifically, enteric fermentation, manure management, rice cultivation, agricultural soils, prescribed burning of savannahs and field burning of agricultural residues are all listed as sources which will have to be taken into consideration by countries in their reports to the Conference of Parties of anthropogenic sources and sinks.

The Kyoto Protocol also makes provision for a Clean Development Mechanism, with the double purpose to assist developing parties in achieving sustainable development and developed parties to achieve

compliance with their emission limitations and reduction commitments. The Clean development mechanism will allow Annex 1 Parties and Non-Annex 1 Parties to jointly implement projects, which will result in certified emission limitations. This mechanism complements the tradable permit approach between Annex 1 Parties.

Needless to say, the implementation of both tradable permits and the Clean Development Mechanism will require a detailed inventory of sources and sinks, regular reporting as well as review and control mechanisms, which certainly will require improved methodologies to assess emissions and sinks.

Incidentally, Article 10 repeatedly resorts to the wording ‘environmentally sound technology’, otherwise used only once in the Protocol and once in the UNFCCC under 4.5. A discussion of the links and differences between environmentally sound technology and the concept of sustainability would be interesting.

There are also commitments in the Protocol for countries to formulate national and regional programmes to improve scientific co-operation, education and training programmes, inventories of emissions and sinks, and to improve, next to mitigation, the adaptation potential. There is also an insistence on the need for developed parties to assist developing ones.

#### 4.2. *Convention on Biological Diversity (CBD)*

The Convention on Biological Diversity (CBD) was opened for signature at the Earth Summit in Rio de Janeiro, Brazil, on 5 June 1992. It entered into force on 29 December 1993. The Convention, which is based on a broad ecosystem approach, contains three national-level obligations: to conserve and sustainably use biological diversity and to share its benefits. The First Session of the Conference of Parties was held at Nassau, Bahamas from 28 November to 9 December 1994.

Several Articles in the Convention, in particular Articles 6 (conservation and sustainable use), 7 (identification and monitoring), 8 (in situ conservation), 12 (research and training), 17 (exchange of information), 18 (technical and scientific cooperation), and 25 (subsidiary body on scientific, technical and technological advice) are of interest to agrometeorology.

Every cubic centimetre of the biosphere has been altered by human-induced changes in the climate and

the chemical composition of the atmosphere and this carries major implications for biological diversity. On the other hand, together, plants, animals and microbes absorb and break down pollutants; help maintain a benign mix of gases in the atmosphere; regulate the solar energy the earth absorbs; moderate regional weather and rainfall; modulate the water cycle, minimizing floods and drought and purifying waters. Hence it is clear that there are major interactions between climate and biological diversity.

The current decline in biodiversity is largely the result of human activity. Despite mounting efforts over the past two decades, the loss of world biological diversity, mainly from habitat destruction, over-harvesting, pollution, and the inappropriate introduction of foreign plants and animals continued.

Forest ecosystems are vital for biological diversity as they provide the most diverse sets of habitats for plants, animals and microorganisms, holding the vast majority of the world's terrestrial species. This diversity is the fruit of evolution, but also reflects the combined influence of the physical environment and people. Forests and forest biological diversity play important economic, social and cultural roles in the lives of many indigenous and local communities. Deforestation, which occurred at significantly higher rates in temperate zones in the past and is now proceeding at alarming rates in the humid tropical regions, can greatly disturb the dynamic coupling between forest and atmosphere that once sustained a unique regional climate and biological diversity.

The carbon that plants pull from the air may be returned to the atmosphere quickly, as microbes or animals that consume fruit, leaves, algae, and other plant material oxidize the carbon compounds to fuel their life processes and breathe CO<sub>2</sub> back to the air as a waste product. Forests already hold most of the land's carbon stores, including 80% of the above ground carbon and 40% of the carbon locked up in the litter, soils, peat and roots. The amount of carbon a forest can take up depends among other factors on climate. It will be important to study the extent of influence of projected climate change on the carbon sequestration by the forests.

A better understanding of the climate of the major ecosystems of the world where biological diversity is at risk could help develop effective in situ conservation strategies. Generally speaking, any natural

resource conservation measures to maintain land productivity through sustainable agricultural practices could effectively contribute to the maintenance of biological diversity.

#### 4.3. *United Nations Convention to Combat Desertification (UNCCD)*

The scale of desertification also referred to, as 'dryland degradation' is immense. The total area of arid, semi-arid and dry sub-humid drylands cover 40% of the Earth's land surface. Vast areas of these drylands, somewhere between 1 and 3.6 billion ha are thought to be suffering some degree of degradation. The areas affected encompass over 100 countries and some 900 million people, who may be suffering from the adverse social and economic impacts of dryland degradation.

Desertification became recognised as a major worldwide issue following the disastrous droughts in the Sahel during the early 1970s. This led to the United Nations Conference On Desertification (UNCOD) in Nairobi in 1977, which formulated the Plan of Action to Combat Desertification. An important outcome of the Earth Summit in 1992 was an agreement to draw up an International Convention to Combat Desertification, which was elaborated by the Intergovernmental Negotiating Committee on Desertification (INCD) and finally agreed in June 1994. This Convention recognises that the desertification issue is on a par with other global issues such as climate change and loss of biological diversity. The United Nations Convention to Combat Desertification (UNCCD) entered into force on 26 December 1996. As of 30 November 1998, 144 countries submitted their instruments of ratification.

The following areas identified in the Convention could be of specific interest to agrometeorology:

1. Incorporation of long term strategies to combat desertification and mitigate the effects of drought in the national action programmes.
2. Enhancing national climatological, meteorological and hydrological capabilities and the means to provide for drought early warning.
3. Establishment and/or strengthening, as appropriate, of early warning systems, including local and national facilities and joint systems at the sub-regional and regional levels.

4. Strengthening drought preparedness and management strategies, including drought contingency plans at the local, national, sub-regional and regional levels, which take into consideration seasonal to interannual climate predictions.
5. Development of sustainable irrigation programmes for both crops and livestock husbandry.
6. Strengthening the capabilities for assessment and systematic observation, including those of meteorological and hydrological services, and for capacity building, education and public awareness.
7. Early warning and advance planning for periods of adverse climatic variation in a form suited for practical application by users at all levels, including especially local populations. To this end facilities for the collection, analysis and exchange of information, as well as for systematic observation will be strengthened at all levels, which shall, inter alia aim to use compatible standards and systems; encompass relevant data and stations, including in remote areas; use and disseminate modern technology for data collection, transmission and assessment on land degradation.
8. Ensuring that the collection, analysis and exchange of information addresses the needs of local communities and those of decision makers, with a view to resolving specific problems, and that local communities are involved in these activities.
9. Contributing to increased knowledge of the processes leading to desertification and drought and the impact of, and distinction between, causal factors, both natural and human, with a view to combating desertification and mitigating the effects of drought, and achieving improved productivity as well as sustainable use and management of resources.
10. Making inventories of relevant traditional and local technology, knowledge, know-how and practices and their potential uses with the participation of local populations, and disseminating such information, where appropriate, in cooperation with relevant intergovernmental and non-governmental organizations.
11. Encouraging and actively supporting the improvement and dissemination of such technology, knowledge, know-how and practices or of the development of new technology based on them.
12. Training of decision-makers, managers, and personnel who are responsible for the collection and analysis of data for the dissemination and use of early warning information on drought conditions and for food production.

#### 4.4. *World Food Summit Plan of Action*

The World Food Summit (WFS), which was hosted by FAO in Rome in November 1996, prepared the WFS Plan of Action with the main objective to improve food security at all levels, and to significantly reduce the number of undernourished people.

Poverty is seen as one of the main factors behind food insecurity, but the WFS document stresses the links between poverty and such factors as natural disasters and climate related ecological changes. Climate fluctuations are indeed the main factors which prevent a regular supply and availability of food, the key to food security.

The WFS elaborated seven Commitments, of which Commitment 3 (sustainable policies and practices essential to adequate and reliable food supplies and to combat pests, drought and desertification) and, to a lesser extent Commitment 5 (prevent and prepare for natural disasters and man-made emergencies and to meet transitory and emergency food requirements), are very relevant for the climate community in a sustainable development perspective.

Commitment 3 makes repeated reference to climate and climate change (including the UNFCCC) and the related problems of desertification, the loss of biodiversity, the depletion of the ozone layer, which are all related, at least indirectly, to the unsustainable use of climate resources. This Commitment stresses the need to promote the research needed to continue international efforts to develop, disseminate and apply climate forecast information that will increase sustainable agricultural, fisheries and forestry productivity and be of particular benefit to developing countries.

Commitment 5 emphasises the need to maintain, promote and establish the preparedness strategies and mechanisms, including development and application of climate forecast information for surveillance and early-warning, drought, flood, other natural disasters, pest and disease alertness. It also underlines the need to support international efforts to develop and apply climate-forecast information to improve the effective-

ness and efficiency of emergency preparedness and response activities, with special efforts to create synergy and avoid duplication.

## 5. Other items of Agenda 21

The Statement of Forest Principles on the management, conservation and sustainable development of all types of forests also carries principles/elements that are relevant to agrometeorology. In the light of the recent forest fires in Indonesia, application of early warning systems in the management and conservation of forests assumes particular significance.

Chapter 32 of Agenda 21 calls for more active role for farmers in influencing decisions. Agrometeorologists should take steps to promote more direct participation of farmers in agrometeorological field studies and in designing appropriate strategies for the provision of agrometeorological information to the users.

## 6. Response of the Commission for Agricultural Meteorology (CAgM) of WMO to UNCED challenges

United Nations Agencies responded, as appropriate to their mandates, to the UNCED challenges identified earlier in the paper. The Commission for Agricultural Meteorology (CAgM) of the World Meteorological Organization (WMO) took appropriate steps to keep its members informed about the developments with respect to UNCED. These included periodic circular letters from the President of CAgM to the Commission members, recommendations for possible activities during the intersessional period of the Commission and appointment of Joint Rapporteurs of the Commission on UNCED Follow-up. The Joint Rapporteurs examined the UNCED challenges relevant to the mandate of the Commission and determined the implications of such challenges and activities on the WMO Agricultural Meteorology Programme and on the work of CAgM.

A comprehensive report prepared by the Joint Rapporteurs of the Commission was submitted for discussion and decision at the 12th Session of CAgM (Accra, Ghana, February 1999). The report presented examples of National/Regional UNCED follow-up relevant to agricultural meteorology for both devel-

oped and developing countries. A summary of proposals for new areas of CAgM activities in response to UNCED is presented in Table 2.

CAgM responses to UNCCD, UNFCCC, CBD and the Statement of Principles on Forests included information exchange through periodic circular letters from the President of the Commission to the members; establishment of Working Groups on (a) Desertification and Drought and (b) Relationships between Weather/Climate and Sustainable Agricultural Production and Protection; Rapporteurs on the Effects of Climate Change and Variability on Agriculture and Forestry; Joint Rapporteurs on the Effects of Climate Variability and Climate Change on Agriculture and Forests — Agrometeorological Aspects of Management Strategies and Improvement of Sustainability; Joint Rapporteurs on Validation of Information Requirements on Forest Management and Exploitation and Rapporteurs on Weather and Climate Related to Forestry and (Non-Forest) Tree Production.

## 7. Towards sustainable agriculture in the 21st Century — priorities for agrometeorologists

Agricultural research until the 1980s was preoccupied with issues of increased productivity to feed the growing populations and the success of green revolution in many developing countries had its foundations in increased use of external inputs such as improved seed, fertilizers, water, pesticides, fungicides etc. As we move into the 21st century, the agricultural research community is faced with the challenge of balancing the continuing need for increased productivity with the new and growing concerns regarding the sustainability of the high-input agricultural production systems and environmental degradation as highlighted by the three international Conventions and the World Food Summit Plan of Action. This points to a new and important role for agrometeorologists around the world and some of the priority areas that need to be addressed are outlined further.

### 7.1. *Improvement and strengthening of agrometeorological networks*

The international Conventions clearly emphasize the need for strengthening meteorological networks

Table 2  
Summary of Proposals for New Areas of Commission for Agricultural Meteorology (CAgM) Activities in Response to UNCED Documents

UNCED Document	Proposals for New Areas of CAgM Activities
United Nations Framework Convention On Climate Change (UNFCCC)	<p>a) Strengthen research in the area of climate prediction and services to agriculture; improve methods for monitoring occurrences of drought and heavy rainfall; develop methodology for assessing socio-economic effects of weather/climate variability on food production; study interactions among climate, drought and desertification, agricultural technology and resource management; develop climatic indicators to be used in research on minimizing adverse impacts in countries with extreme climate variability; develop a comprehensive model for predicting changes in greenhouse gas emissions associated with different management practices in agricultural and forestry systems.</p> <p>b) Facilitate capacity building for climate prediction.</p> <p>c) Enhance management and exchange of information and networking including maximum use of available CLIPS products.</p>
Convention on Biological Diversity (CBD)	<p>a) Maintenance of land productivity through adoption and use of sustainable agricultural farming systems.</p> <p>b) Provision of support services and post-harvest facilities.</p> <p>c) Management and conservation including rehabilitation of critical resources through 'ecosystem approaches'.</p> <p>d) Efficient use of agricultural lands through promotion of research and development on the utilization of indigenous materials in pest control.</p> <p>e) Maintenance of optimum level of land dedicated to agricultural use.</p>
United Nations Convention to Combat Desertification (UNCCD)	Creation of a drought information system with capabilities for international network access.
Statement of Principles on Forests	<p>a) Encourage provision of information on proper resource management.</p> <p>b) Develop network for exchange of information.</p> <p>c) Encourage Members to promote rapid reforestation and proper management to arrest further erosion, especially near water reservoirs.</p> <p>d) Develop capacities for planning assessment and systematic observation of forests.</p> <p>e) Develop basic information related to area and type of forests and the existing potential and volume of harvest.</p> <p>f) Conduct research on use of agrometeorological information in efficient, rational and sustainable development and utilization of forests and forest-based resources and on activities that are non-degrading and have value-added component to forests such as wildlife conservation.</p>

to support data collection for research into the interactions between climate and the particular aspect addressed by the Convention e.g., drought and desertification by the UNCCD. Although agrometeorological networks have been in operation for many years now, in many developing countries and in some countries in transition, these networks are falling into disrepair due to lack of sustained funding for their maintenance and operation. As more emphasis is now being placed on vulnerable regions including those in remote areas, a re-evaluation and global support of the existing networks to respond adequately to the needs of the priority regions and priority research areas such as sources and sinks of greenhouse gases is essential. It is

also important to integrate the deployment of modern technologies, such as automatic weather stations, for data collection and transmission in the re-evaluation of existing networks.

### 7.2. *Development of new sources of data for operational agrometeorology*

Recent developments in remote sensing such as detection of soil moisture, estimation of evapotranspiration, rainfall etc., constitute new sources of data for many agrometeorological applications. These not only complement ground observations, but also offer new types of data (like those of microwave satellites),

provide global coverage and can often be used to improve ground data e.g., in area averaging. It is important to take appropriate steps to promote the collection and use of these data in operational agrometeorology. This is one area where regional and global cooperation can help countries that lack the financial and technical resources to acquire such data.

### *7.3. Improved understanding of natural climate variability*

In certain agroecological regions of the world, such as the semi-arid tropics, climatic control of soil water availability through rainfall and evaporation is most prominent and inter- and intra-annual variability of rainfall is perhaps the key climatic element that determines sustainable agriculture in these regions. Both the UNFCC and the UNCCD emphasize the need for research into a better understanding of climate variability in order to be able to assess the impact of and the distinction between, causal factors, both natural and human, for climate change, drought and desertification. This points to the need for undertaking surveys and research to establish the needed baseline information. A better understanding of the climate of the major ecosystems of the world where biological diversity is at risk could help develop effective in situ conservation strategies.

### *7.4. Promotion and use of seasonal to inter-annual climate forecasts*

One of the persistent demands of agriculturists is the provision of reliable forecasts of seasonal climate as it would help them take appropriate decisions as to which crops/cropping systems should be chosen well ahead of the sowing rains to avoid undue risks. Agenda 21 as well as the WFSPA emphasize strongly the application of climate forecast information for increased and sustainable agricultural production. Agrometeorologists should make efforts to promote more active use of seasonal to inter-annual climate forecasts in agricultural planning and operations.

### *7.5. Establishment and/or strengthening of early warning and monitoring systems*

The role of early warning and advance planning for periods of adverse climatic variation in a form

suitable for practical application by users at all levels, especially at the local level, has been emphasized by Agenda 21, UNCCD and WFSPA. In this context, the application of climate forecast information to improve the effectiveness and efficiency of emergency preparedness and response activities is essential. There is also a need for methodological work on the monitoring side, in particular regarding the identification of critical thresholds that should trigger early warnings. This issue is linked to forecasting e.g. given the history that leads to a given situation, do we forecast that it will become critical, if so how critical and when, and how many people, are going to be affected.

### *7.6. Promotion of geographical information systems and remote sensing applications and agroecological zoning for sustainable management of farming systems, forestry and livestock*

Agroecological zoning offers much scope for developing strategies for efficient natural resource management and in this context, recent advances in the geographical information systems and remote sensing have made the task of integration and mapping of a wide range of databases much easier. Also the determination of agroclimatic production potential using these approaches can help in more efficient agricultural planning.

### *7.7. Use of improved methods, procedures and techniques for the dissemination of agrometeorological information*

Rapid advances made in the recent past in information technology, especially in audio-video media, need to be quickly operationalized to more effectively diffuse agrometeorological information to the user community. Here the development of a bottom-up approach of the full involvement of users is important to ensure that the methods and procedures so developed will adequately respond to the appropriate needs of the users.

### *7.8. Development of agrometeorological adaptation strategies to climate variability and climate change*

Food and fibre production is perhaps the sector most sensitive and vulnerable to climatic fluctuations. There

is a clear need to identify the priority agrometeorological adaptation strategies for regions that are identified as being most vulnerable to the effects of climate variability and climate change and quickly diffuse this information to such regions.

#### 7.9. *Mitigation of the effects of climate change*

The prevailing philosophy regarding climate change mitigation, particularly in developing countries and at the subsistence farming level, has been one of 'no-regrets' i.e., only measures that make economic sense now should be adopted, because they reduce emissions from the agricultural sector or improve resilience of all sectors of agriculture against weather variability. All have a marked management component and could thus often be implemented at minimal cost.

Of direct relevance to agrometeorologists, next to improved fertiliser use, and improved ruminant digestion, one could mention the development of water harvesting and conservation techniques, as well as other improvements to crop-water management as an adaptation to rainfall variability and the growing of alternative energy crops in substitution of fossil fuels. These have to be agroclimatically efficient and properly balanced against food crops.

#### 7.10. *More active applications of models for phenology, yield forecasting etc.,*

Although almost all current models were originally developed for modeling a crop at the scale of a field, some of them are being used at the level of countries and even of the planet in global change impact studies. Model use for a particular purpose depends on whether its complexity is appropriate to the question being asked and whether the model has been tested in diverse environments (Boote et al., 1996). The opportunity exists for the use of non-parametric and rule based models as well as process-oriented models with outputs as probability density functions.

#### 7.11. *Active promotion of tactical applications such as response farming at the field level*

Operational decision making during the growing season could be promoted by more active promotion

of tactical applications such as response farming at the field level, both in the developing as well as the developed countries. Recent developments in precision farming, flex-cropping, etc. in the developed countries hold much promise for future applications at the field level.

#### 7.12. *Promoting a better understanding of the interactions between climate and biological diversity*

Although CBD does not make a direct reference to agrometeorology, it is clear that there are quite a few implications of climate variability and climate change to biological diversity. Hence it may be useful to undertake an authoritative review of the interactions between climate and biological diversity. It will be important to review the effect of changes in the regional climate on deforestation and their impact on biological diversity. As this paper is emphasizing the linkages between agrometeorology and sustainable agriculture, reviews or case studies on how sustainable agriculture practices would contribute directly or indirectly to biological diversity may be quite useful.

## 8. Conclusions

The steady increase in human populations and periodic droughts in many areas around the developing world have caused food shortages, put stress on the resource base and have jeopardized the long term sustainability of these agricultural production systems. In the light of the projected 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.

Sustainable development is a philosophy which sets a long-term goal that can only be achieved by a set of management practices. All the major international conventions, to which most countries are now committed, emphasize that countries should implement policies aimed at greater sustainability. The almost poetic decision as to whether sustainability is one or the other thing is now mostly irrelevant: it has become a policy that must be enforced using appropriate management practices.

Development of sustainable food production strategies requires a more complete understand-

ing of the limitations of the ecosystem and of the inter-relationships between crops, trees and livestock. Proper incorporation of agroclimatic considerations in the development of improved strategies requires a much longer time frame than has been used in the past. 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 and determining the impact of sustained use of a given production system on the resource base.

Given the complexity of the agricultural production systems, the task of ‘matching’ an improved system with the physical environment is not easy. It is imperative that more emphasis should be placed on multi-disciplinary research that brings together agroclimatologists, agronomists, soil scientists, agroforesters, and livestock specialists. A well coordinated research thrust with emphasis on resource management will better serve the cause of sustainability in the long run. In this connection, several important priorities for agrometeorological applications have been highlighted in the three international conventions and the World Food Summit Plan of Action. These present important challenges and great opportunities for agrometeorologists to play a pro-active role in promoting sustainable development in the 21st century.

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