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AGROMETEOROLOGICAL INFORMATION FOR AGRICULTURAL SYSTEMS
SUBJECTED TO CLIMATIC VARIABILITY

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INTRODUCTION

In the last twenty years the research in the field of Agrometeorology has progressed in a huge way due to the progress in the measurement technics and to the trend in the basic agricultural, biophysical and ecological research.

Nevertheless the operational applications are for the time being not yet largely diffused all over the world.

We can try to summarize the reasons why in the following considerations:

1)- We learnt a lot about the micrometeorological processes but the great variability of the meteorological parameters does not allow us to apply the knowledges with the high degree of accuracy requested by the biological systems. There are not well defined methodologies to turn from the mesoscale to the toposcale and from this to the microscale.

2)- We have not a large data bank on the reply of species and varieties to meteorological factors neither standardised methodologies to measure these characteristics. This situation is particularly deficient in the field of fruit trees and vegetables.

In addition to these causes, related to the world of research, many great changes have taken place in this period:

a)- Interest for agriculture in developed countries has decreased meanwhile the interest for global change of environment has increased.
b) - Definition of global change is not very often clear enough.

c) - Deficiency in agricultural production in developing countries is increased dramatically in comparison with the rate of population increasing.

d) - The environmental conditions of developing countries are becoming worst than in the past due to overexploitation and to wrong cultural practices.

e) - There is at least the danger that important changes in the climate due to the human activities should take place.

All these facts have some feedbacks on the international and national organization of research activity and on funding of research projects related to agrometeorology and ecology.

Starting from these considerations and from the state of art of the incoming technologies as informatics, remote sensing, electronics, our Institutions started ten years ago a reflexion that is always on the way, to address the research strategies for the future.

The possibility to apply the knowledges in operational way both in developed and developing countries is related to the following steps:

1) - Definition of the purposes of agrometeorological practice and consequent outputs.

2) - Definition of spatial and temporal accuracy of inputs and outputs.

3) - Organization of informations in a GIS to rely them to the
land pattern.

4) Data processing and modelling for output producing.

These steps ask for a procedure well defined in which many technical competences should cooperate for the final product; the establishment of this procedure has been one of the main goals of our Institutions during the last ten years.
LISA

LAND INFORMATION SYSTEM FOR AGRICULTURE
1) - GENERALITY

Many study activities have been undertaken in order to establish the most convenient operations for environmental managing and planning; in any case, an essential condition that must be satisfied before taking any decision is the availability of a complete set of information about territorial characteristics.

Since such a set includes a very large amount of data to be managed, a tool for this purpose is necessary too. For this reason, the Geographic Information Systems were created and in a very short time they have assumed a basic role for territorial management and planning.

About ten years ago, the activity of a section of the I.A.T.A. (Institute for Environmental Analisys and Remote Sensing for Agriculture) of National Research Council and, under an applicative point of view, of the Ce.S.I.A. (Center for Application of Informatics in Agriculture) of the Accademia dei Georgofili, began, following this need, to develop an aimed system that, once set up, has been continuously upgraded, so that at this time it is no more a G.I.S., even if complete, but more exactly an Integrated Territorial Information System; this means that every kind of information about territory, coming from whatever source, can be elaborated. Besides, many applicative packages are already included for the standard processing and the modular structure of the whole system allows to add others which are aimed to face specific problems.
2) - GENERAL CHARACTERISTICS OF L.I.S.A. SYSTEM

L.I.S.A. system was thought to reply to these demands:

The methodology, and consequently the operative software, of L.I.S.A. Information System is organized in packages and each of them performs a complex set of processes; every package is once more divided in modules in charge for specific operation.

At this time, the whole system is written in Fortran 77 language and it runs on a minicomputer Digital Vax 3900 in VMS operating system; specific input/output peripherals (digitizer, plotter, pictoric monitor) are of course available.

Implementation of versions running both in Window environment on workstations Digital and in Unix environment, C language, on workstation SUN is in progress; a semplified version for PC is also foreseen (fig. 1).
LISA - LAND INFORMATION SYSTEM FOR AGRICULTURE
(General outline)

METEO P.
DIGITAL AND ANALOGICAL METEOROLOGICAL DATA
CLIMATIC DATABASE
ESTIMATE OF MISSING VALUE
STATISTICAL ELABORATION
PRINT OUT

DTM P.
ANALOGICAL MAPS DIGITAL MAPS
MORPHOLOGIC DATABASE
COMPUTE OF DTM
1 2

PEDO P.
SPATIAL AND NONSPATIAL SOIL DATA
SOIL DATABASE
LAND USE INVENTORY
2

IMAGE P.
REMOTELY SENSED IMAGES
IMAGE PROCESSING
ESTIMATE OF METEOROLOGICAL PARAMETERS
1

AGROCLIMATIC CLASSIFICATION
ESTIMATE OF PRODUCTIVITY AND OTHER PURPOSE
1

GEOSYS P.
WATER BALANCE
2
THEMATIC MAPS
PRINT OUT
3) - OBJECTIVES

The main objectives of L.I.S.A. System can be summarized as following:

- AGROCLIMATIC AND BIOCLIMATIC CLASSIFICATION
- AGRICULTURAL POLLUTION MAPS
- PEST AND DISEASE CONTROL
- WATER RESOURCES
- IRRIGATION PLANNING
- AGRICULTURAL CHANGE INDUCED BY CLIMATE CHANGE
- ENVIRONMENTAL MANAGEMENT
- LAND CAPABILITY AND SUITABILITY

\[
\begin{align*}
\text{AGRICULTURAL CENSUS} & \quad \begin{cases} 
\text{CLASSIFICATION} \\
\text{MORPHOLOGICAL} \\
\text{LAND USE} \\
\text{POTENTIAL AND ACTUAL PRODUCTIVITY} \\
\end{cases} \\
\end{align*}
\]

agricultural and environmental census to assess the crops inventories, the abandoned areas, the forestry areas, the ratio between green and concrete areas, the crop yields, the meteorological adversities and damages, the forest biomass and for soil erosion and degradation.
Applicative packages running at the present are the following:

**METEO** Managing and processing of meteorological database, with production of outputs both in graphic (thematic maps) and numerical (tables) form; last ones are used as input for other modules of the system.

**DTM** Creation of digital terrain model; slope, aspect, global theoretic radiation computing; managing and processing of morphological data base.

**PEDO** Managing and processing of pedological data base; soil water balance computing (by revised SWATRER model).

**IMAGE** Remote sensing images processing; data from satellites with different spatial/spectral resolution and from airplane platform are considered. The purpose is to obtain a land use inventory and an estimation of agrometeorological parameters on regional scale.

**GEOSYS** Chartographic editing for thematical maps output, in conjunction of numeric explanation.

4.1) **METEO APPLICATIVE PACKAGE**

It is based on DBMS (Data Base Management System) that manages a meteorological database including data from about 1000 stations on the whole Italian territory. Data regard 40 years (starting from 1951) of daily measurements of rainfall, tempera-
ture (max. and min.), global solar radiation, wind (speed and direction), humidity, taken by Ministry of Works and National Meteorological Service networks. The database is periodically updated.

The whole set of information is georefered by a file including all the information about the stations (latitude, longitude, altitude, hydrographic basin etc.) necessary to their geographic localization.

The database allows selective access to data archives for statistical processing or simply for original data visualization.

4.1.1) - Data geographic interpolation

Available meteorological data are measured in a single point, that is they represent the situation in a very small area around the station. If the goal is the climatic characterization on territorial scale, it is necessary to extrapolate the information on the areas not directly covered by measurements. In order to get this result, a methodology for automatic interpolation has been developed.

The spatial variation of a given meteorological parameter depends basically on two factors: distance and morphology. About the first one, the more the examined point is far from the station (source of data), the less the measured data are representative of the situation in this point. The interpolation module takes in account this factor using a pre-determined grid and assigning to each station an area including a number of grid elements at the shortest distance compared with any other station. The area so defined is called "competence area". The radius in which
the research is carried out depends on the characteristics of the territory and on the dimension of the grid.

The so obtained matrix of elements is overlapped to the digital terrain model and modified taking in account the morphology.

Finally, temperature and radiation are corrected according to the altitude and the aspect.

4.1.2) - Missing data estimation

Radiation and humidity data are very often missing, at least in widespread quantity; this makes difficult the application of simulation and classification methodology. For this purpose, two methods for the estimation of daily values of global radiation and humidity, based respectively on daily thermal range and presence/absence of rainfall and minimum temperature, have been developed.

4.1.2.1) - Method for estimation of global solar radiation

Radiation data are not very often available in sufficient quantity, so it is necessary to try to estimate them starting from other parameters that can be easily found.

As it is well known, the total amount of global radiation on a horizontal surface is a function of the day, latitude, atmospheric conditions and cloudiness. During clear sky days, it is possible to compute radiation using geographic (latitude) and astronomic (solar declination) data; atmospheric extinction effect can be computed taking in account water vapour and aerosol contents. In this way it is possible to obtain global radiation for
clear sky condition, but it is very hard to calculate extinction
effect when it is cloudy, also considering that cloudiness data
are measured in a real small number of stations. A method for
this purpose has been developed.

It is based on some considerations about energetic balance
of earth surface; net radiation (incoming radiation - reflected
radiation) is divided between latent heat and sensible heat; the
last causes the air heating. As during the night air humidity
goes to saturation, the minimum temperature nearly coincides with
wet point temperature. Starting from night minimum level, tempe-
range increasing is due principally to net radiation. Conside-
ring daily thermic range, it is possible to estimate the value
of daily global radiation and, starting from data measured in so-
me meteo stations, it is possible to obtain a formula to calcula-
te it, taking in account also morphological information. Besides,
it has been found a formula to compute the effect of water vapour
and atmospheric variability.

4.1.2.2) - **Method for average daily vapour pressure estimation**

The methodology is based on some considerations about earth
radiation balance and thermal behaviour of earth surface and at-
mosphere. As a matter of fact, earth loses heat in the form of
infrared radiation; the higher is the loss, the lower is the con-
tent of water vapour in the atmosphere. The result is a progres-
sive cooling of the surface and of the air of its boundary layer.

The atmospheric cooling causes the increase of relative hu-
midity and, the more the relative humidity increases towards the
saturation value, the more heating loss is reduced by the absor-
ption of microscopic water drops of condensation; this phenomenon
begins on surfaces with temperature lower than the atmospheric one, considering that these surface are bodies emitting in the IR region.

As a conclusion, the value of minimum temperature, during most of the nights, goes to, in terms of time, the maximum value of relative humidity and this one is very close to the saturation value.

Starting from these considerations, it is possible to compute the value of vapour pressure.

Since water vapour content in the atmosphere is determined by air characteristics, in order to estimate the value of vapour pressure during the day it is necessary a "filtering" of the variations due to the influence of more or less wet quantities of air; this can be done substituting the average value of vapour pressure between i-st and i+1-st day to that one calculated as it is illustrated above.

4.2) - APPLICATIVE PACKAGE DTM

It is based on specific modules for the acquisition and the processing of cartographic data; generally, I.G.M. (Military Geographic Institute) standard cartography, scale 1:25.000, has been used, but it is possible to get information from any other.

Acquired geographical elements are contourn lines and topographic information as roads, rivers, urban areas, administrative boundaries and so on.

The referring system Gauss-Boaga was chosen, but also in
this case it is possible to use any other because a conversion module is included in the system.

The altitude information are used, by computing procedures, to obtain slopes and aspects; these three kind of data constitute the digital terrain model (DTM).

The whole set of processing is in raster format, to make easier the overlapping with remote sensing images, that are delivered in this format.

4.3) - APPLICATIVE PACKAGE IMAGE

Most part of input data of G.I.S. are traditionally coming from papers that are acquired in manual or automatic way. At the present, the use of remotely sensed data (by satellite or airplane) is getting more important, because of the possibility to obtain spatial information in a faster way.

In particular, satellites with high-resolution sensors, as Landsat and SPOT, are very good for land use classification, while meteorological satellites, as those of NOAA series, have shown to be adapt for the estimation of some parameters as surface temperature, thermal inertia, evapotranspiration and large-scale yield forecasting.

Landsat 5, a satellite of third generation, equipped by the high-resolution sensor Thematic Mapper (TM), shows the best qualities for agricultural and forestry monitoring; as a matter of fact the TM sensor has some characteristics that make it very
suitable for cover types discrimination: high spatial resolution (30 m.) joint to large enough spectral coverage (7 bands including infrared), good separation between bands, that are quite well centered on peaks of reflection, absorption and emission of vegetation.

To utilize these characteristics at the best, some methodologies have been developed, especially aimed to face troubles due to coverage fragmentation and shadow effect; in any case, use of G.I.S., able to merge and manage in integrated way remotely sensed data and any other kind of territorial information, has shown to be the key-tool to solve several problems.

Meteorological satellites, in particular those of NOAA (National Oceanic and Atmospheric Administration) have shown good possibilities of application besides of their original goals.

The AVHRR (Advanced Very High Resolution Radiometer), installed on most recent NOAA platform, can provide, by means of thermal infrared channel, information about surface temperature at regional scale and in different moment of the day; in this way it is possible to estimate some agrometeorological parameters that can integrate ground measurements.

The NDVI index (Normalized Difference Vegetation Index), obtained by combination of some bands, have been demonstrated to be a good indicator of general environmental conditions and, consequently, a time-integrator of ecological factors, such as temperature and rainfall.

This package includes also an interface module to GEOSYS package that allows the cartographic representation of processed remotely sensed images; these can be in this way overlapped to
other cartography, getting thematic maps or allowing further processing to obtain summarizing of thematiques.

4.4) - APPLICATIVE PACKAGE P E D O

This is based on a DBMS that manages a database including many information, regarding several soil characteristics, and on a model for soil hydrological balance.

In the L.I.S.A. system the hydrological balance is processed by a module based on SWATRER model software (Laboratory of Soil and Water Engineering-Leuven, Holland); it is a simulation model of water balance and vertical fluxes in saturated and unsaturated soil conditions.

The model needs the description of physical properties of soil profile as input; a detailed description of humidity profile and fluxes for each day of the elaboration is given as output.

Required parameters, that are included in input charts created by an aimed module, are the following:

a) - **Physical parameters of soil** - number of layers in the soil profile; soil moisture/pressure head and pressure head/conductivity curves.

b) - **Bottom boundary conditions** - some options are available to define the bottom boundary condition in saturated (water table present) or unsaturated (flux at bottom, free drainage etc.) soil.

c) - **Root water uptake** - soil moisture critical values for root water uptake at both high and low evaporative demand of at-
mosphere; maximum root uptake/depth curve; root depth.

d) - **Upper boundary conditions** - Meteorological parameters (precipitation and irrigation, evaporation, transpiration, rain interception by leaves); runoff (by SCS Curve Number Method).

e) - **Initial conditions** - soil moisture profile at the beginning of elaboration.

The general lack of information about soil (just a small-scale cartography is very often available) has led to the implementation of a database including tensiometric curves of most common soil types. This kind of parametrization allows running of model even if the whole set of necessary data is not available for a chosen area, because it is possible to use options reasonably more similar.

If no information about soil of study area are available at all, a standard soil type is considered for the whole zone.

4.5) - **APPLICATIVE PACKAGE**  **G E O S Y S**

This is practically the G.I.S. of the whole system L.I.S.A.; it is utilized to realize thematic maps starting from data matrices coming from other packages, completed by results of processing in table form.

It is also oriented to acquiring of data, both in graphical and numerical form; as L.I.S.A. System, it is structured in paka-
ges, each of them performs specific functions.

4.6) - USER - SYSTEM INTERFACE

Modules can be run both by on-line commands and tree-structured menu'; in the first case it is possible to build up specific applications which are not included into menu'. The system is in this way very flexible and easily adaptable thanks to parametric files directly modifiable by edit procedures.
5) - PRESENT SYSTEM APPLICATIVE PERFORMANCES

At the present, the system performs the following operations:

1)- Agroclimatic classification: it is obtained by determination of omogenous climatological areas, with regard to specific agrometeorological parameters. This methodology has been applied in several case studies, and in particular, in applicative form, for the classification of the whole Toscana and Abruzzo Regions.

2)- Potential productivity estimation: several potential productivity indices are used; in particular, one of them was developed by Ce.S.I.A. and applied in some areas in order to be tested for applicative purposes.

3)- Risk maps by agricultural pollutants: by using a whole set of information (morphology, pedology, land use, well localizations, water table depth), it is possible to perform a weighted summary that can produce a "risk value" represented by a map. This methodology has been applied in some areas in collaboration with Public Institutions, both Governmental and Regional.

4)- Morphological terrain classification: by the same method of weighted summary, it is possible to obtain a division in morphological omogenous areas of the territory, starting from the information of D.T.M. (altitude, slope and aspect). A practical application was performed in collaboration with the Provincia of Florence in order to take a census of agricultural farms.
Assessment of ecological interrelations by means of an integrated land information system

A methodology based on the use of the integrated land information system L.I.S.A. has been put forward to assess the influence of ecological factors on the distribution of vegetated cover surfaces. The methodology has been applied to a case study concerning a hilly zone of Tuscany of about 10X10 Km. south of Florence, corresponding to a geographic map 1:25.000 scale. The area, which is mainly covered by deciduous woods, olive groves and vineyards, is placed on a gently undulated terrain, with altitudes ranging from 100 m. to 700 m. (fig. 2-9)

A precise land use inventory has been obtained from multi-temporal Landsat 5 TM by means of an advanced classification procedure, and three major ecological factors (elevation, exposure and soil type) have been taken into consideration. The quantitative assessment of the influence of each factor has been performed by the use of mutual information analysis and frequency histograms. The method has allowed the definition of the importance of the ecological factors examined, useful also as a basis for land suitability studies.
Figura 1. - Funciones de rendimiento de maíz simuladas para seis niveles de lluvia (mm) en la región de El Bajío, México (Villalpando, 1983).
Fig. 2
ALTITUDE CLASSES

TOTAL AREAS 9984 HA
ASPECT CLASSES

- NORTH: 12.2%
- NORTH-EAST: 15.0%
- EAST: 11.4%
- SOUTH-EAST: 6.5%
- SOUTH: 10.7%
- SOUTH-WEST: 13.8%
- WEST: 16.0%
- HORIZ. PLANE: 16.7%

TOTAL AREA: 9684 HA

Fig. 4
LAND USE

1 PINEWOOD (Maritime pine)
2 CHESTNUT TREES
3 DENSE OAK (Quercus pubescens e Quercus cerris)
4 CLEAR OAK (Quercus pubescens e Quercus cerris)
5 VINEYARD
6 OLIVE GROVE
7 BUILT-UP AREAS

TOTAL AREA 9984 HA
SOILS ASSOCIATION

1-2-3 LEACHED SOILS ON ALLUVIAL DEPOSIT
4-8 RED MEDITERRANEAN SOILS ON SANDSTONE
5-7 RED MEDITERRANEAN SOILS ON HOLOCENE
   ALLUVIAL DEPOSIT
6 RED MEDITERRANEAN SOILS ON "ALBERESE"
9-10 RED MEDITERRANEAN SOILS ON MARLS
11 RED MEDITERRANEAN SOILS ON "ARGILLE SCAGLIOSE"
12 BROWN MEDITERRANEAN SOILS ON MARLS
13-14 BROWN MEDITERRANEAN SOILS ON SANDSTONE
15 GRAY BROWN PODZOLIC SOILS ON ALLUVIAL DEPOSIT
16 BROWN ACID SOILS ON SANDSTONE
17 BROWN ACID SOILS ON SLATE

TOTAL AREA 9984 HA
PINEWOOD

SOIL

ALTITUDE

ASPECT

RELATIVE FREQUENCY
AGROCLIMATIC CONSIDERATIONS FOR SUSTAINABLE AGRO-SILVI-PASTORAL SYSTEMS IN THE SUDANO-SAHELIAN ZONE

M.V.K. Sivakumar, C. Renard and J.M. Powell

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Agroclimatic Considerations for Sustainable Agro-Silvi-Pastoral Systems in the Sudano-Sahelian Zone*

M.V.K. Sivakumar, C. Renard and J.M. Powell**

Abstract

The Sudano-Sahelian zone (SSZ) of West Africa with uncontrolled population growth, decreasing agricultural productivity and continuing food deficits, is one of the most critical regions of the world. The productivity of the Agro-Silvi-Pastoral (ASP) systems combining trees, crops and animals which proved sustainable since long, is now threatened. A review of selected definitions of sustainability clearly emphasize natural resource management and conservation. This paper reviews some of the agroclimatic considerations in developing strategies for sustainable ASP systems. Some traditional ASP systems in the SSZ are described. Analysis of historical climatic data for physical constraints points to extreme variability of rainfall in time and space; irregular growing season lengths; intermittent dry spells; high temperatures and wind erosion; and inadequate soil and water management practices as important constraints. Methodologies are now available that enable assessment of rainy season potential and intra-seasonal droughts for evaluating cropping risks. Studies on the physical, chemical and hydraulic properties of soils help understand the soil resources and their constraints, and in evolving strategies for exploitation of soil and climatic resources in the SSZ. The management of sustainable ASP systems should be oriented towards efficient natural resource use and includes strategies such as the choice of appropriate crop varieties and animal types; adoption of intercropping and relay cropping systems including pearl millet/legume associations, millet/forage legumes, Faidherbia albida systems, mixed tree, grass and crop systems; rotations; use of crop residues; and integrated use of manures and a limited quantity of fertilizer. Evidence of the benefits of employing such strategies is presented through field studies conducted in the SSZ. Some relevant issues concerning efficient resource use for sustainable agriculture in the SSZ have been discussed.
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., 1987). It is however incontestable that sustainable agriculture is seen as an important goal throughout the world. Rapidly rising population 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 now 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 than long term sustainability.

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

There is no generally accepted definition of sustainable agriculture (CGIAR, 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 (NRI, 1991). The enhancement of the environmental quality and 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 literature (Table 1) show that natural resource use is a keyword in almost all of them.

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. For the sake of discussion of the issues involved in sustainable agriculture, we are using examples from the Sudano-Sahelian zone (SSZ), which extends over several countries of West Africa. It is one of the poorest regions of the world with subsistence agriculture as the main mode of livelihood. Over 90% of the population lives in villages. Decades ago, with fewer people to feed, farmers were able to maintain the fragile natural resource base by utilizing pastoral animal systems and shifting agriculture for crop production. But growing population pressures combined with shortened fallow cycles and continuous cultivation, extended droughts since 1969 and successive crop failures resulted in a decline in the per capita food production. Hence sustainable agriculture to feed the growing populations has become an issue of major concern in the SSZ.

Agro-Silvi-Pastoral Systems in the Sudano-Sahelian Zone

The SSZ is probably very unique of all the climatic zones in the world because of the nature of coexistence and mutual dependence of man, trees, crops and livestock in this region for centuries. Agro-Silvi-Pastoral (ASP) systems combining trees, crops and animals have proven to be valuable and sustainable over many years (Le Houérou, 1989). ASP systems can be quite variable according to climatic conditions, socioeconomic constraints, types of vegetation and crops. The challenge of sustainability is critical for these systems because a majority of them are located on marginal lands with low productivity.

Role of trees in ASP systems

Ideally in the ASP systems, multipurpose trees are predominant. They contribute to soil fertility by recycling nutrients from deep zones, procure wood for fuel or building, can give edible fruits and medicines, and produce forage for feeding the livestock. Beside their useful products, they can play a major role in the control of runoff and wind erosion, improve the environment by shading and lowering the soil temperatures, and facilitate water infiltration.
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<th>Definition of sustainability/ sustainable system(s)</th>
<th>Keywords for agroclimatic information</th>
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| American Society of Agronomy (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.                                                                                     | Management of resources  
Natural resource base  
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.                                                                                                                                                                                                                               | Natural resources  
Exploited resources                                                                                                                                                                          |
| COIAR/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                                                                                                                                                                                    |
| Davis and Schirmer (1987)     | Among the topics considered under sustainable agriculture are resource management issues dealing with soils, land, natural resources and water sheds; 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                                                                                                                                                                             |
| Knezeck 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.                                                                                                                                                                                                                | Resource conserving  
Environmentally sound                                                                                                                                                                        |
| Lai (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.                                                                                                                                                           |
<table>
<thead>
<tr>
<th>Author</th>
<th>Definition of sustainability/ sustainable system(s)</th>
<th>Keywords for agroclimatic information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lynham and Herdt (1988)</td>
<td>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.</td>
<td>(resources for) maintaining output</td>
</tr>
<tr>
<td>Okigbo (1991)</td>
<td>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.</td>
<td>Resource base</td>
</tr>
<tr>
<td></td>
<td>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.</td>
<td>Ecologically sound, Management of resources</td>
</tr>
<tr>
<td>Rodale (1988)</td>
<td>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.</td>
<td>Self-generating production resources</td>
</tr>
<tr>
<td>Rome Forum (1986)</td>
<td>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.</td>
<td>Ecological conditions</td>
</tr>
<tr>
<td>Ruttan (1989)</td>
<td>Development of technology and practices that maintain and/or enhance the quality of land and water resources.</td>
<td>Land and water resources</td>
</tr>
<tr>
<td></td>
<td>The improvement in plants and animals and the advances in production practices that will facilitate the substitution of biological technology for chemical technology.</td>
<td></td>
</tr>
<tr>
<td>UCED (1987)</td>
<td>Conserving and enhancing the resource base and merging economics and environment in decision making are among the objectives for sustainable development.</td>
<td>Resource base</td>
</tr>
</tbody>
</table>

The major output of trees — the foliage, the pods and the fruits — constitute an important source of feed for the livestock particularly at the end of the dry season when stocks of crop residues are exhausted. Breman and de Wit (1983) showed that with increasing annual rainfall from 50 to 1000 mm, mean production of biomass increases from nearly 0 to 4 t/ha. According to Bille (1980), foliage biomass of trees and shrubs in the semi-arid tropics increases very rapidly when rainfall is above 200 mm with maximum forage production at 1500 kg/ha at 1500 mm rainfall (Fig. 1). Out of this total biomass, the portion available to the browsing animals varies from 100% to 5.7% according to the height of the tree (Hiermaux, 1980). Farmers or herders will lop the trees and it affects the production according to the severity of trimming and the species (Cissé, 1980).
Figure 1. Productivity of trees as a function of climate (After Bille, 1980).

In Mali, Hiernaux (1980) gives figures for annual feed (browse) potential of ligneous species. This potential is a little below half the corresponding grass production of natural grasslands (Table 2). The palatability of this feed varies according to the livestock, the tree species, and the time of the year.

<table>
<thead>
<tr>
<th>Ecological regions and sectors</th>
<th>Live delta (Farimaké de) (de Peroudji)</th>
<th>Dead Delta</th>
<th>Continental shelf</th>
<th>Whole area*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sahelian</td>
<td>South Sahelian</td>
<td>Sahelian</td>
<td>South Sahelian</td>
</tr>
<tr>
<td>Average per sector of DM t/ha</td>
<td>0.27</td>
<td>0.50</td>
<td>0.75</td>
<td>0.70</td>
</tr>
<tr>
<td>Per sector estimate of DM '000 t/ha</td>
<td>100</td>
<td>425</td>
<td>560</td>
<td>763</td>
</tr>
</tbody>
</table>

* North Sudanian sectors excluded.

Role of livestock in ASP systems

By keeping livestock, farmers minimize risks in an agroclimatically variable environment. Animals can be sold during years of poor crop production thereby stabilizing food availability. During years of very low crop productivity, or complete crop failure, animals are key to household survival. Livestock also provide an important investment opportunity which stabilizes the income of farmers and provides cash for cropping needs (seeds, fertilizer, labour etc).

There are numerous agronomic benefits associated with mixed farming. Animal manures are the most commonly used soil fertility amendment and are vital to the sustained productivity of many cultivated areas. In more intensively managed farming systems, animal traction provides transport, alleviates labour
shortages and increases crop yields. Cropland forages, especially crop residues, provide important feeds for animals, especially during the 6 to 8 month dry season. Animal weight gains are greatest during the post harvest, crop residue grazing period (Fig. 2).

![Graph showing seasonal weight changes of female sheep and goats in Burkina Faso](image)

**Figure 2.** Seasonal weight changes of female sheep and goats in Burkina Faso (Adapted from Bourzat and Wilson, 1989).

### Types of traditional ASP systems

In the SSZ, pearl millet and sorghum are the crops grown largely by the subsistence farmers and are usually intercropped with a legume, such as cowpea (*Vigna unguiculata* L. Walp.), groundnut, or sorrel (*Hibiscus sabdariffa* L.). For example, in the Nigerian savanna, Norman et al. (1982) found virtually no sole-crop millet, although millet mixtures occupied about one-third of the cultivated area. Moving northward to the Sahel zone, the proportion of sole cropping increases. In villages of the Sahelian region of Niger, the proportion of sole cropping rises to 30-50% (ICRISAT 1986). Traditionally farmers sow low plant populations, about 5000-7000 hills ha⁻¹.

In some regions of the Sahel, between the isohyets 500-1000 mm, farmers combine the cultivation of pearl millet, groundnut and cowpea with orchards of *Faidherbia albida* (Del.) Chev. Such systems, as described by Pélissier (1966) in the Serer region of Senegal, permit high densities of population, permanent cropping with rather high yields and an additional one or two head of smallstock per hectare (Le Houërou, 1989).

Another ASP system -- quite common in Sudan, Chad and Niger -- is based on about 20 ha of family owned land which is subdivided into four sections for rotation every five-six years. These rotations include:

- **Years 1-5:** Plantation of gum trees, *Acacia senegal* (L.) Willd. and pearl millet is cultivated between the trees.
- **Years 6-10:** First harvest of gum arabic from the trees, cutting grass from fallow land;
- **Years 11-15:** Period of full yields of gum arabic, controlled grazing possible between trees;
- **Years 16-20:** Final harvest of gum arabic, clear felling of the acacia trees, grazing.
The rotation continues with replanting and agricultural use in the 21st year for five to six years. Depending on site quality and rainfall, these 20 ha can maintain a family of 5-10 people (Advisory Committee on the Sahel, 1983). The sustainability of this system is due to the long fallowed period which favors the restoration of soil fertility (Baumer, 1987). With the increasing demographic pressure, the length of the gum tree period has been shortened and soil fertility can no more be maintained.

Other common ASP systems include the “Zarma system” in Niger (Sidikou, 1974) and the “Dogon system” in Mali (Gallais, 1965). The Zarma system is a good example of a traditional system able to cope with a harsh environment. The land owned by the village is divided in circles going from the village center to the outside. The first circle (Haul) is intensively cultivated and manured, gombo and other vegetables are grown, a few trees (Tamarindus indica L., F. albida) are kept for their monetary value. In the second circle (Koiraté) millet is grown for 6-7 years and fallsow alternates with cultivated lands. Many trees (Acacia nilotica (L.) Willd, Balsamites aegyptiaca (L.) Del., F. albida, Sclerocarya birrea (A. Rich.) Hochst.) are kept for fodder or other uses. The third circle (Zighi) is extensively cultivated and not as well managed as the Koiraté circle. Beyond that area, one finds the forest. This system has been greatly modified with the increasing demographic pressure resulting in forest devastation.

In Mali, the Dogon had to establish themselves on the abrupt slopes of the Niger river, since the plain had been taken over by the Mossi and the Peuls. They developed an integrated system of terrasses, ridges, manuring, transport of alluvial soils and park of useful trees. There is a close integration of trees, crop and animals.

These ASP systems were formerly possible since the population and animal pressure were lower than at present. The communal and social structures were such to ensure a production equilibrium where trees played an essential role. Quite intensive, these systems are or were characterized by a dynamic cycling of materials and energy. Changes occurring with the colonial period, increases in human and animal populations, and recent droughts deeply modified these systems. People started exploiting the existing more and more forests, that were already poorly managed, herdsmen brought their cattle in these wooded lands impairing the regeneration of trees, farmers extended their cultivated land, and fallsow almost vanished. As a result, degradation of land by collan or water erosion increased, soil nutrient status went down and the capacity of the fragile ecosystem to resist degradation collapsed.

People adapted themselves by shifting from traditional practices of nomadism, shifting cultivation, and specialization in crops or livestock to more sedentary and integrated systems, often referred to as traditional systems in the literature.

Importance of Agroclimatic Considerations in Sustainable Agriculture

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. 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 recent 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.

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 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 cannot germinate when it is sown in soil. This is because biological entities, such as crops, are not abstract entities, but a producer of their temporal and genetic history in varying environments (Senanayake, 1991) and there are lethal environmental thresholds which an organism cannot transcend (Hart, 1957). Many of the ecological implications of agricultural development requires 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. 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 accelerate 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.

This increased awareness of the need for sustainability perspective has also led to changes in the research programs. For example, at many of the International Agricultural Research Centers (IARCs), the 'Farming Systems Research Program (FSRP)' gave way to the 'Resource Management Program (RMP)', with increased emphasis on resource characterization and applications. The primary objective of RMP is to develop systems of production which match material from the crop improvement programs to the physical and social environments (ICRISAT, 1987). 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.

Towards Sustainable ASP Systems in the Sudano-Sahelian Zone

Steiner et al. (1988) addressed the issue of improving and sustaining productivity in dryland regions and categorized the constraints into four categories: physical (agroclimatic conditions and soil characteristics), technological (soil fertility, crop germplasm, and production constraints), institutional and infrastructure (credit, marketing and distribution, research and technology transfer, fertilizers and pesticides, and farm-level knowledge base) and socioeconomic (population growth, land tenure and fragmentation, role of women, pastoral grazing, lack of labor, and macroeconomic policy). Although agroclimatic considerations are important in alleviation of constraints in all the four categories, clearly the first two -- physical and technological -- merit a closer look and this paper places emphasis only on these two.

Understanding physical constraints through analysis

According to Baier (1990), the physical determinants, which have a significant impact on productivity and sustainability are soil (soil erosion and soil fertility), water (irrigation and rainfall), atmosphere (acid rain, CO₂, greenhouse effect, desertification), hazardous chemicals and energy (fossil fuels, natural gas, coal, uranium). Given the present situation in the SSZ, the major physical constraints that should be considered are rainfall, soils and desertification. In defining the future role for sustaining the resource base of an expanding agriculture in the semi-arid regions, Stewart et al. (1989) placed emphasis on efficient management of rainfall and on arresting the degradation of soil resource base. Although not mentioned by Baier (1990), high temperatures and damaging winds should also be listed among the constraints in the SSZ.
Variability of Rainfall in Time and Space

In the SSZ, agriculture is predominantly rainfed. Because of the concentration of rainfall in a single rainy season extending over 3-4 months and a protracted dry season for the rest of the year, timely onset of rainfall and its regular distribution through the rainy season are critical for the success of the rainfed production systems. Droughts are set off by rainfall deviations that fall far below the average rainfall. Rainfall in this zone is low, variable, and unpredictable. Temporal and spatial variations are so large that agricultural systems in the marginal conditions become vulnerable to such variations. Annual rainfall variations at three locations in the SSZ, Filingue, Niger (mean annual rainfall, 420 mm), Dedougou, Burkina Faso (840 mm) and Kita, Mali (1020 mm) show clearly the problem of variability (Fig. 3). Rainfall variability around the mean is more pronounced at Filingue, the lower rainfall location (Fig. 3a), in comparison to Kita (Fig. 3c) with a higher mean annual rainfall.

An important feature of the Sudano-Sahelian rainfall is the magnitude and extent of the rainfall deviations. Below normal rainfall could persist for 10-20 years. For example, between 1969-89 Dedougou, Burkina Faso (Fig. 3b) has been consistently dry and rainfall deviations exceeded 50% of the mean rainfall. Also, rainfall fluctuations in the SSZ are associated with a preferred geographic pattern. For example, the reduction in the mean annual rainfall in Niger after 1969, was a geographical mean pattern, not an isolated or patchy occurrence (Sivakumar 1989a).

Variability within the rainy season is much larger since the rainfall is usually limited to a few months i.e., May to October. Rainfall variability is greatest at the daily scale. Number of rainy days as well as the average rainfall per rainy day increase from May and reach the maximum by August.

An aspect that is intriguing about the climatic variability in the SSZ is that the decline in rainfall in the past two decades appears to have occurred in the most important period of the rainy season i.e., August, when the crop water needs are usually at their peak. For example, using five-year moving averages of August rainfall for selected locations in Niger, Sivakumar (1991a) showed a clear decrease in rainfall over the period 1965-88 (Fig. 4). As opposed to the natural ecosystems, agricultural production systems are man made and hence are more vulnerable to such changes in rainfall. The seasonal nature of crop production makes agriculture even more difficult because in Niger, where the rainy season is already short, even a moderate decline in rainfall could result in complete crop failure. In the grazing systems, reduced biomass production in poor rainfall years could mean overgrazing resulting in complete denudation of soils that leaves them vulnerable to wind erosion in the following years leading to land degradation and desertification.

The characteristic high rainfall variability in the SSZ causes large inter- and intra-annual differences in agricultural productivity. The short, 4 to 5 month rainy season provides few choices for cropping other than the drought resistant cereals i.e., sorghum and millet; and cowpeas. Uneven seasonal rainfall distribution causes an uneven distribution in the availability of fodder which limits livestock productivity. Animals typically lose 20 to 30% of their weight during the dry season as forage availability diminishes (Fig. 2). Animals may continue to lose weight during the beginning of the wet season as initial rains spoil dried forages remaining from the previous wet season. During dry seasons following poor rainfall, carrying capacities may be greatly reduced requiring that animals trek long distances to more humid areas further south.

Sustainable gains in crop and livestock productivity in the SSZ have been greatly hampered by inadequate rainfall. Two major droughts over the past 20 years have had profound negative effects on agricultural productivity. In Niger, for example, crop and animal production decreased dramatically during the droughts of the early 1970’s and mid 1980’s (Fig. 5). Human population has continued to increase, however, at approximately 2.5% per annum during this period.

The expansion of cropping has been the most common response for augmenting food production. During the post drought period of the mid 1970’s the rate of bringing new land under cultivation has been much faster than population growth, causing severe stress on the land resource base (Boulier and Jouve, 1990). Opening new areas to cultivation has not had a sustained positive impact on overall crop productivity. Grain yields per unit area have apparently decreased over the past 20 years (Fig. 5).
Figure 3. Variations in the mean annual rainfall along with the 5-year moving average and long term average rainfall at Filingue (Niger), Dedougou (Burkina Faso) and Kita (Mali).
Figure 4. Variations in the 5-year moving means of August rainfall at selected locations in Niger.

Figure 5. Human and livestock populations, cultivated areas and grain production in Niger, 1960-88 (Adapted from Marche Tropicaux, 1983)
Length of the growing season

Rainfall variability shown in Figure 3, specially at Filegue (Niger), sets the limit to the cropping season and hence determines the cropping systems which are practiced. Because of such unpredictable rainfall patterns, agricultural planning should revolve around an approach that considers actual or intraseason weather conditions. Agroclimatological methodologies developed recently showed that historical daily rainfall data could be analyzed for indicators to forecast the season rainfall category, and then using the forecast to guide farm management decisions (Stewart, 1982; Sivakumar, 1988). Even at locations such as Filegue with low average annual rainfall (420 mm), years with more favourable rainfall distribution do occur (Fig. 3a) and it is necessary to strive for product-maximizing strategies in such years. Hence early identification of the 'potential' for each year is a very important step in designing appropriate strategies for increased food production in the SSZ.

From a study of parameters such as the onset of rains and the length of the growing season, which are important for decision making, Sivakumar (1988) showed that it is possible to predict the rainy season potential in the SSZ from the date of onset of rains. To exploit this potential, a methodology termed "Weather-responsive Crop Management Tactics" was suggested. This is based on the finding that the onset of rains is much more variable than the ending of rains. For example, for 30 locations with mean annual rainfall ranging from 350-640 mm, the average date of onset of rains was 23 June with a standard deviation (s.d.) of 17 days while the average date of ending of rains was 12 September with a s.d. of 9 days (Sivakumar, 1989b). Therefore, an early onset of rains offers the probability of a longer growing season while delayed onset results in a considerably shorter growing season. Hence the potential of the growing season can be assessed with reference to the date of onset of rains. This is illustrated in Tables 3-5 for Filegue, Dedougou and Kita (data base 1945-1989). The dates of onset of rains in these tables for computation of probabilities are so selected as to cover 20 days before and 20 days after the mean dates of onset of rains, approximately one standard deviation from the mean date of onset of rains. At Filegue (Table 3) with lower mean annual rainfall, if the onset of rains occurs early i.e., by 17 June, there is a 37% probability that the growing season will exceed 100 days. On the other hand, if the rains are delayed till end of July, even for a 60 day growing season length the probability is only 38%. At Dedougou (Table 4) and Kita (Table 5), early onset of rains offers excellent prospects for the growing season duration to exceed 150 days and hence the potential exists at these locations for diverse cropping strategies.

Simple methods of analysis such as those described above could be used for tactical decision making within the growing season for sustaining desirable production levels.

Length of dry spells

Although the date of onset of rains provides an idea regarding the potential of the growing season, questions still remain on the nature of the distribution of rainfall within the growing season. When are droughts most likely to occur and in the growing season and what is the expected length of the droughts? Long term daily rainfall data could be analyzed to answer such questions. Sivakumar (1991b) used the specific definition of onset of rains for each year as the sowing date and computed the length of dry spells (or days until the next day with rainfall greater than a defined threshold value) and the percentage frequencies of dry spell lengths for 150 locations in the SSZ.

The lengths of dry spells for Filegue, Dedougou and Kita at 90% probability level for the 10 mm rainfall threshold are shown in Figure 6. The data show that at 60 DAS, in 9 out of 10 years, the dry spells will end after 4.5 days at Kita and 6.1 days at Dedougou, while at Filegue one has to wait for 18.2 days for the dry spells to end.

The implication of the above analysis is that in terms of crop phenology, dry spells from the stages of emergence to panicle initiation (up to 20 DAS) and grain filling last longer than those during panicle initiation to flowering (20-60 DAS).

High temperatures and evaporation rates

Because of the long dry season that precedes the early rains of the rainy season in the SSZ, the soils
Table 3. Probability of growing season length exceeding specified durations for variable onset of rains at Filingue, Niger.

<table>
<thead>
<tr>
<th>Date of onset of rains</th>
<th>Length of growing season (days) exceeding</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60</td>
</tr>
<tr>
<td>14 Jun</td>
<td>99</td>
</tr>
<tr>
<td>24 Jun</td>
<td>96</td>
</tr>
<tr>
<td>4 Jul</td>
<td>86</td>
</tr>
<tr>
<td>14 Jul</td>
<td>65</td>
</tr>
<tr>
<td>24 Jul</td>
<td>44</td>
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</tbody>
</table>

Table 4. Probability of growing season length exceeding specified durations for variable onset of rains at Dedougou, Burkina Faso.

<table>
<thead>
<tr>
<th>Date of onset of rains</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>110</td>
</tr>
<tr>
<td>30 Apr</td>
<td>100</td>
</tr>
<tr>
<td>10 May</td>
<td>99</td>
</tr>
<tr>
<td>20 May</td>
<td>94</td>
</tr>
<tr>
<td>30 May</td>
<td>80</td>
</tr>
<tr>
<td>9 Jun</td>
<td>58</td>
</tr>
</tbody>
</table>

Table 5. Probability of growing season length exceeding specified durations for variable onset of rains at Kita, Mali.

<table>
<thead>
<tr>
<th>Date of onset of rains</th>
<th>Length of growing season (days) exceeding</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>110</td>
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<td>11 May</td>
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<td>21 May</td>
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<tr>
<td>31 May</td>
<td>95</td>
</tr>
<tr>
<td>10 Jun</td>
<td>76</td>
</tr>
<tr>
<td>20 Jun</td>
<td>50</td>
</tr>
</tbody>
</table>
Figure 6. Average lengths of dry spells during the crop growing season at Fillingue (Niger), Dedougou (Burkina Faso) and Kita (Mali).

are usually very dry in the beginning of the rainy season. Also, the major soil types in the SSZ have a high propensity to compaction and hardening during the dry season (Nicou and Charreau, 1985). Also environmental conditions during the stage of crop establishment in the SSZ, especially in the low rainfall areas, are usually harsh. Air temperatures at this time are usually higher because of the high radiation load. From south to north temperatures increase as rainfall decreases. From the analysis of the frequency distribution of air temperatures, Sivakumar (1989a) showed that mean maximum temperatures could exceed 40°C at the time of sowing and that absolute temperatures could be much higher. Although one or two showers facilitate sowing, the soil moisture evaporates quickly and if a period of dry, clear weather follows, the soil surface temperatures rise rapidly up to 55°C. Under these conditions, the young seedlings face a lot of heat stress.

One of the major constraints for farming operations, specially on the Arenosols, is the rapid rate of drying of soil after a rain, because of the high rates of soil evaporation. These conditions demand rapid land preparation for sowing and very efficient methods of planting.

In view of the short growing season and the farmer's limited capacity in terms of available power, the number of days available for preparatory tillage prior to the optimum date of sowing is an important issue. Long term daily rainfall data could be analyzed to provide information of this nature. Hoogmoed (1986) concluded that the size of rainfall showers relevant for decision making with regard to preparatory tillage is fairly predictable, and one could calculate the total number of days available for preparatory tillage and for sowing. For Niamey, Hoogmoed and Klaaij (1990) showed that the total number of workable days is 31 and the average number of plantable days does not exceed 10 days. This analysis shows that the speed with which planting operations can be carried out is an important issue and use of animal traction is one of the ways to ensure this.

Wind erosion

In the SSZ, wind as a climatic factor has a significant effect on soil productivity. Use of marginal lands for cultivation, overgrazing, and removal of trees and shrubs over the past two decades, has created
conditions that have accentuated wind erosion. The role played by livestock and small ruminants in this process is now being increasingly recognized. The intensive grazing practice with animal trampling leaves the soil surface bare and compacted during much of the fallow period, and highly vulnerable to wind erosion. Generally lower rainfall in the last two decades combined with such practices might have led to problems of increasing wind erosion and decreasing visibility as shown from data at two locations in Niger (Fig. 7). As compared to the 60s, during the 80s there was a significant increase in the number of days with poor visibility (visibility < 5 km) at the two locations. This problem is becoming particularly serious at the beginning of the rainy season, rains are usually preceded by dust storms, with violent winds that can exceed 100 km h\(^{-1}\). This contributes to erosion and millet which is usually sown with the first rains in May or June, is damaged by wind abrasion or by burial under sand, often leading to a total loss of young seedlings.

![Graphs showing days with visibility < 5 km in Niamey and Tahoua, Niger.](image)

**Figure 7.** Changes in the visibility from the 1960s to 1980s at Niamey and Tahoua in Niger.

The combination of high temperatures and sand blasting in the beginning of the growing season usually lead to problems of crop establishment. While the recommended plant population for millet on the sandy soils of the SSZ is around 30,000 plants/ha, on the farmers' fields the populations are usually much lower. The farmers are often forced to replant their crops, sometimes up to 3 or 4 times in the same rainy season.

Despite the wide recognition of the problems associated with wind erosion, there is very little effort devoted to quantifying the sand blasting effects on crops of the SSZ. From the stand point of agroclimatological information, it will be useful to determine the probabilities and establish the confidence limits for predicting duration and intensity of meteorological conditions conducive to wind erosion (Skidmore, 1988). Measurement made with dust sampling stations at ISC during 1990 showed that the amount of sand trapped decreased exponentially with height above the soil surface (Fig. 8). Beyond 75 cm height, it was less than 1% of that at 10-cm height, though the distribution at different heights differed with the erosion event. For one sand storm, 384 g of sand was measured at 10 cm height, which was about 30% of the sand trapped during the entire season at that height. These data help in making decisions about the height of wind breaks that could be used to reduce the wind speeds and trap the sand so as to protect the millet crop.

In trials conducted at ISC, low wind breaks such as *Andropogon gayanus* Kunth. (65 cm height) and *Bauhinia rufescens* Lam. (155 cm height) trapped up to 60% of the sand at 15 cm above the soil surface (ICRISAT, 1990). Such perennial grasses and fodder shrubs serve multiple purposes for the farmer of soil conservation, shelter belts, animal fodder as well as material for construction of huts.

**Soil Resources and Water Balance**

One of the basic problems with the use of broad climatic zones such as SSZ for sustainable agriculture is that it may convey a sense of homogeneity. In reality, the term SSZ hides a diversity of crop growing environments. From the point of sustainability therefore, it is important to recognize the diversity of soils in the SSZ because soil is also an important factor relating to the development of sustainable agricultural systems. Major soil types and their extent in the SSZ, computed from the FAO-UNESCO soils map of Africa (1977), are shown in Table 6. Arenosols and Luvisols are the two major soil types in the SSZ accounting for 56% of the total area.
Figure 8. Accumulated sand captured at different heights above the soil surface, ISC, Sadore, growing season 1990.

The effectiveness of the low and variable rainfall in the SSZ is further dictated by the soil type and its physical and chemical properties. A recent analysis of 31 soil samples from the major millet growing regions of the SSZ showed (Table 7) that the total sand content varied from 71.99% with a mean of 87%. These soils are prone to production constraints imposed by physical and climatic processes e.g. crusting, drought, erosion by wind and water, and high soil temperatures. One striking feature of these soils is the inherently low soil fertility, which is expressed through their low levels of organic matter, total nitrogen, and effective cation exchange capacity.

Much of the recent research in the SSZ indicates that rainfall per se is not necessarily the crucial limiting factor to agricultural production, rather it is the proportion of rainfall which enters the soil moisture reservoir and its subsequent utilization by plants. Arenosols have a low moisture holding capacity which imposes a severe drought risk if extended dry periods occur during the crop growing season. On the other hand, Luvisols present a different management problem because of their tendency to form a hard crust on the surface resulting in reduced infiltration and increased runoff. Charreau (1972) showed that as much as 32% of the mean annual rainfall could be lost as runoff on a well-tilled, cropped Luvisol while on a bare soil the losses could be as high as 60%.

It is common knowledge that similar amounts of rainfall, on dissimilar soil types, could lead to different levels of available water for crop growth. At Bengou in southern Niger, measured soil water profiles in two soil types, a loam and a sandy loam, at the time of planting and harvesting of millet during the 1986 growing season (Sivakumar and Wallace, 1991) showed important differences with the same seasonal rainfall of 784 mm. Hence strategies for sustainable agriculture may have to be site-specific. Although simple causal relationships between rainfall and tree or pasture productivity have been shown (as in Fig. 1), it is more appropriate to consider the complete water balance of the system that includes rainfall, runoff, drainage, available water storage, evaporation and water uptake by plants. The concept of water balance helps to determine the effective length of the growing season and how the different components in an ASP system could be selected to match this growing season length.
Table 6. Major soil units and their approximate extent in the Sudano-Sahelian zone (Source: Sivakumar 1989a)

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Approximate extent (m ha)</th>
<th>Percent of total area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luvisols</td>
<td>42.3</td>
<td>31.7</td>
</tr>
<tr>
<td>Arenosols</td>
<td>32.2</td>
<td>24.2</td>
</tr>
<tr>
<td>Regosols</td>
<td>19.7</td>
<td>14.8</td>
</tr>
<tr>
<td>Vertisols</td>
<td>9.5</td>
<td>7.1</td>
</tr>
<tr>
<td>Lithosols</td>
<td>8.2</td>
<td>6.2</td>
</tr>
<tr>
<td>Fluvisols</td>
<td>6.5</td>
<td>4.8</td>
</tr>
<tr>
<td>Gleysols</td>
<td>3.2</td>
<td>2.4</td>
</tr>
<tr>
<td>Notosols</td>
<td>2.9</td>
<td>2.1</td>
</tr>
<tr>
<td>Planosols</td>
<td>2.8</td>
<td>2.1</td>
</tr>
<tr>
<td>Cambisols</td>
<td>2.6</td>
<td>1.9</td>
</tr>
<tr>
<td>Other soils</td>
<td>3.6</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Table 7. Means and ranges of selected physical and chemical properties of millet-producing soils of the SSZ (Source: ICRISAT 1991)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH H₂O (2:1 water:soil)</td>
<td>5.2 - 8.2</td>
<td>6.3</td>
</tr>
<tr>
<td>pH in KCl</td>
<td>4.0 - 7.5</td>
<td>5.1</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>0.7 - 11.7</td>
<td>3.6</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>71.3 - 99.0</td>
<td>87.3</td>
</tr>
<tr>
<td>Organic matter (%)</td>
<td>0.08 - 2.94</td>
<td>0.75</td>
</tr>
<tr>
<td>Total nitrogen (mg kg⁻¹)</td>
<td>31-1800</td>
<td>266.0</td>
</tr>
</tbody>
</table>

Exchangeable bases (cmol kg⁻¹)

<table>
<thead>
<tr>
<th>Element</th>
<th>Range</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>0.15 - 16.5</td>
<td>2.45</td>
</tr>
<tr>
<td>Mg</td>
<td>0.02 - 2.16</td>
<td>0.55</td>
</tr>
<tr>
<td>K</td>
<td>0.03 - 1.82</td>
<td>0.24</td>
</tr>
<tr>
<td>Na</td>
<td>0.02 - 0.09</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Exchangeable Al (cmol kg⁻¹)

<table>
<thead>
<tr>
<th>Element</th>
<th>Range</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.00 - 14.51</td>
<td>1.60</td>
</tr>
</tbody>
</table>

Effective cation exchange capacity

<table>
<thead>
<tr>
<th>Element</th>
<th>Range</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.54 - 19.20</td>
<td>3.10</td>
</tr>
</tbody>
</table>

Proceedings of a recent International Workshop on Soil Water Balance in the SSZ (Sivakumar et al. 1991) present several examples of the application of simple soil water balance models that are now available for use on microcomputers. Computer programs such as INSTAT (Stern et al. 1991) facilitate easy computations of soil water for quick applications. An example of such calculations is shown in Figure 9 for Filingue, Dedougou and Kita. Superimposition of the water requirement curve for a given crop/cropping system on such graphs enable assessment of risk and frequency of failure. Sivakumar (1988) discussed the methods of integration of soil and crop models for agroclimatic analysis.

**Agroecological Zoning**

One of the useful ways to organize the climate, soil, and crop information for regional applications is the approach of agro-ecological zones. With this approach one can estimate the potentials for crop production in different areas and by superimposing the statistical data on potentials, it is possible to arrive at percentage attainment of potential. In developing strategies for sustainable agriculture, this approach holds much promise.
Figure 9. Rainfall and computed soil water contents using a soil water balance model at Filingue, Dedougou and Kita during the 1985 rainy season (soil water holding capacity assumed as 100 mm).
since it quantifies the extent to which the potential of a region is realized and enables identification of constraints and of appropriate priorities for improvements.

Historically, the methods used ranged from use of simple climatic indices (Thornthwaite, 1948; Hargreaves, 1971; Doorenbos and Pruitt, 1977) to climatic classification systems (Koppen 1936; Thornthwaite, 1948; Troll, 1965). The Agroecological zones project of FAO provided an assessment of the rainfall production potential for Africa (FAO, 1978). In a five-step process, this approach selects potential crops according to temperature zones; calculates the potential productivity based on the length of the growing period and harvest index; reduces the estimated yield due to constraints such as pests and diseases; modifies the yield and crop suitability according to soils; and checks the yields against experimental results.

Currently, the availability of powerful and inexpensive computers make it possible to use methods of storage and analysis that until recently would have been impossible because of the cost and complexity of equipment and methods used. Recent developments in Geographic Information Systems (GIS) opened up new possibilities for agroecological zonation. GIS is a structured framework for acquisition, storage, retrieval and analysis of data within some common spatial referencing system (Nix, 1987). This computer-based methodology including hardware, software, and graphics encodes, analyzes, and displays multiple data layers derived from various sources in a geographically coded mapping format. GIS provides the basis for resource management on scales ranging from the farm level to the regional, provincial and ultimately the national level.

Management of Sustainable Systems

Agricultural productivity tends to increase as systems move from extensive to more intensive modes of production. For millet, higher grain and stover yields are associated with intensively managed silty sand soils that have favorable water regimes (Duivenbooden, 1990). Stall-fed animals gain weight faster than grazing animals (Bourzat and Wilson, 1989). This advantage, however, is likely associated with the additional labour provided to animal management, harvesting and storing feed and providing water to confined animals.

In areas of high demographic pressure, cultivated areas per household are usually smaller than in more extensive production systems, the expansion of cropping reduces fallow periods, and there is a greater reliance on animal manures for sustaining crop yields. In Niger, for example, higher land use intensity and manure application rates are associated with higher rainfall (Table 8). In these areas cattle are more important than sheep and goats. Lower manuring rates in the northern villages is principally due to the increased risk of excessive manure application in low rainfall areas.

Although production gains are made through intensification, the risk of environmental degradation increases when moving from extensive to more intensive modes of agricultural production. As more land is cultivated wet season grazing lands are diminished which can cause feed shortages and over grazing. All crop residues in intensively managed farming systems are usually harvested from fields and fed to stall-kept animals. The continuous removal of vegetation over the long term, however, can increase soil erosion, deplete soil nutrient reserves and lead to decreases in soil, and eventually crop and animal productivity. Hence it is important to develop a set of agronomic management techniques that can ensure sustained productivity while maintaining the natural resource base.

Agronomic and livestock management for efficient natural resource use

Various factors have led to the disruption of the ASP systems in the SSZ and have resulted in the systems being increasingly incapable of maintaining their relationship with the natural environment. Given the limitations with the soils, and the increasing pressures on the land due to growing demands for food production, one generally agrees that no input agriculture is not viable and our role as agronomists or environmentalists is to create or recreate sustainable production systems with low cost, affordable inputs that are acceptable to the farmers of the region. The inputs associated with ASP systems seem to meet such requirements and some well tested options are now available from studies conducted in the SSZ region.

Choice of appropriate crop varieties and animal types

Although the existence of long-term trends in uncertain, it is clear from the discussion on rainfall

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Zones</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wet</td>
</tr>
<tr>
<td>Rainfall (mm)</td>
<td>600</td>
</tr>
<tr>
<td>Cultivated area (ha/household)</td>
<td>3.2</td>
</tr>
<tr>
<td>% manured</td>
<td>29</td>
</tr>
<tr>
<td>Manure dry matter (kg/ha)</td>
<td>3800</td>
</tr>
<tr>
<td>% cattle</td>
<td>52</td>
</tr>
<tr>
<td>% small ruminant</td>
<td>48</td>
</tr>
<tr>
<td>Manure N (kg/ha)</td>
<td>45</td>
</tr>
<tr>
<td>Manure P (kg/ha)</td>
<td>5.7</td>
</tr>
</tbody>
</table>

Variability that the rainfall series in the SSZ contain extended periods of both high and low rainfall. Hence, early maturing cultivars have a better chance of success in years of late onset of rains. Our studies on drought spells showed that at low rainfall locations such as Filingue, millet cultivars that mature in 90-95 days are more likely to avoid the long dry spells during the grain filling phase than the long duration cultivars which mature in 110 days.

In years with good rainfall and above-average growing season length, short duration millet varieties may not be able to fully exploit the favourable moisture situation. Intercropping and relay cropping systems described below offer alternative cropping strategies under such conditions.

Diko and Sayers (1988) working in northern Niger found that many producers lost all animals during the 1984-1985 drought. While rebuilding herds, producers appear to be shifting from cattle to sheep and goats production (Fig. 10). The long reproductive cycle of cattle make their reconstitution longer than sheep and goats. Another response to drought appears to be a shift in livestock ownership and management. More animals are now kept by sedentary agro-pastoralists than transhumant pastoralists, the principal livestock owners prior to recent droughts.

**Intercropping/relay cropping**

Pearl millet/legume association: Farmers in the Sudano-Sahelian region over the years have evolved a mechanism for exploiting the good years by intercropping long season millet with cowpea. Stern (1984) estimates that 80% of the cultivated area in West African tropics is intercropped. Cowpea (*Vigna unguiculata* (L.) Walp) provides grain and hay and the latter can contribute significantly to livestock nutrition by improving the nutritive value of stover (Renard and Garba, 1989).

From a resource use perspective, several agronomic factors such as planting and harvest schedules, crop densities and spacing, soil fertility status and varieties with contrasting durations determine the performance of millet and cowpea in an intercrop situation. Research at ISC showed that manipulation of one or more of these components led to substantial yield increases in the intercropping systems (Table 9). Given the short rainy season in the SSZ, it is important to match the maturity cycles of millet and cowpea to the water availability period. In the traditional combinations a local cultivar of millet is intercropped with a late maturing, photoperiod-sensitive, local cowpea whose flowering coincides with the end of the rains. As a result, local cowpea often faces moisture stress and produces little or no grain when rains terminate early. Substitution of local cultivars of either millet or cowpea by an improved cultivar gave similar yield increases, but maximum
advantage was observed with the use of improved cultivars of both component crops (Table 9). Manipulation of factors such as date of planting of cowpea relative to millet and time of harvesting of cowpea is meant mainly for gaining the maximum temporal advantage of use of resources such as light, water and nutrients so as to enhance the complementarity of growth of both millet and cowpea.

In years with early onset of rains, a complementary system to intercropping is the relay cropping of millet with cowpea for hay. This strategy assumes that the farmers’ aim is to harvest a full crop of millet and any additional cowpea hay. In a field test at ISC, Sivakumar (1990) showed that when the onset of rains occurs early, it is possible to establish a second crop of cowpea for hay. Cowpea enables effective use of the September rains, a large part of which would otherwise have evaporated because of the poor water holding capacity of the soils at ISC and provides valuable hay (and possibly grain if rains continue into October) to the farmer. Sivakumar (1990) showed that the combined water use of millet and cowpea in the relay cropping system approaches the total seasonal rainfall reflecting the maximum use of rainfall (Table 10).

One important issue for research on sustainable agriculture is the nature of the effect of increased cropping intensity, through the intercropping and relay cropping practices described above, on wind erosion. If increased cropping pressure on the soil is not accompanied by appropriate soil and crop management practices, it may well lead to increased problems of soil degradation and threaten sustainable agriculture.

Millet/forage legume: In the SSZ, ruminant livestock are becoming more and more dependent on crop residues for their needs. The poor quality of millet stover has prompted a need for the improvement of the feeding systems that benefit both the farmer and his livestock. Incorporating legumes other than cowpea could provide important protein to livestock and contribute to the improvement of soil fertility through their nitrogen fixing ability.

Among various perennial legumes, *Stylosanthes hamata* (L.) Taub and *S. fruticosa* (Retz.) Alston are particularly well adapted to the short rainy season (Garba and Renard, 1991b). *Stylosanthes* (Stylo) is sown in between millet rows at the rate of 4 kg ha⁻¹. It establishes and sets seed before millet is harvested. After harvest, animals are allowed to graze the stylo and the millet stover. If the stylo has been grazed at ground level, it will not regenerate from plants but from seed the following season. The production of seed is quite
### Table 9. Reported grain yield advantage (%) by agronomic manipulation in intercropping*  

<table>
<thead>
<tr>
<th>Component</th>
<th>Yield advantage (% over control)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fertilizer</strong></td>
<td></td>
</tr>
<tr>
<td>40 kg/ha N</td>
<td>49</td>
</tr>
<tr>
<td><strong>Cultivars</strong></td>
<td></td>
</tr>
<tr>
<td>Local millet x local cowpea</td>
<td>28</td>
</tr>
<tr>
<td>Improved millet x local cowpea</td>
<td>38</td>
</tr>
<tr>
<td>Local millet x improved cowpea</td>
<td>40</td>
</tr>
<tr>
<td>Improved millet x improved cowpea</td>
<td>69</td>
</tr>
<tr>
<td><strong>Date of planting of cowpea relative to millet</strong></td>
<td></td>
</tr>
<tr>
<td>Same day as millet</td>
<td>35</td>
</tr>
<tr>
<td>6 days after millet</td>
<td>24</td>
</tr>
<tr>
<td>25 days after millet</td>
<td>22</td>
</tr>
<tr>
<td><strong>Time of harvesting of cowpea</strong></td>
<td></td>
</tr>
<tr>
<td>40 days after planting</td>
<td>102</td>
</tr>
<tr>
<td>60 days after planting</td>
<td>146</td>
</tr>
<tr>
<td>80 days after planting</td>
<td>94</td>
</tr>
<tr>
<td>End of season</td>
<td>35</td>
</tr>
</tbody>
</table>

*Data compiled from Ntare et al. (1989)*

### Table 10. Grain and hay yields (kg/ha), water use (mm) and water use efficiency, WUE (kg/ha/mm) of cropping systems during the 1986 and 1987 rainy seasons (Sivakumar, 1990).

<table>
<thead>
<tr>
<th></th>
<th>Millet</th>
<th>Cowpea</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grain</td>
<td>Straw</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1986 rainy season</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Early rains</td>
<td>1210</td>
<td>3650</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1987 rainy season</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Early rains</td>
<td>1050</td>
<td>5370</td>
</tr>
<tr>
<td></td>
<td>187</td>
<td>2.6</td>
</tr>
</tbody>
</table>


sufficient, *S. hamata* produces 10-11 kg ha\(^{-1}\) of seed and *S. fruticosa* between 19 and 162 kg ha\(^{-1}\).

In a normal rainfall year, a production of 1.7 t ha\(^{-1}\) of dry matter can be obtained from Stylo and in a good year up to 5 t ha\(^{-1}\) of dry forage was harvested (Garba and Renard, 1991a). The millet/Stylo association makes efficient use of the soil water profile and the water use efficiency is much higher than in the millet/cowpea system. The total biomass, crude protein and P contents of the association were between 1.1 and 3.2 higher than that obtained in the sole millet crop (Kouamé et al., 1991). Sheep feeding trials on pure millet stover or supplemented with Stylo and cowpea hay have shown that average daily liveweights gains of the sheep were significantly increased. Research results from the semi-arid regions of India showed that yield improvement of pearl millet after *S. hamata* is equivalent to an application of 20-50 kg N ha\(^{-1}\).

*Faidherbia albida* systems: Positive effects of *F. albida* on yields of crops grown under the tree canopy have been reported by various authors (Charreau and Vidal, 1965; Dancette and Poullain, 1968, Kessler and Boni, 1991). These effects are largely due to better soil chemical, physical and microbiological characteristics under the trees than outside. Dancette and Poullain (1968) report also that trees affect the microclimate with temperature being lower and air humidity higher under the canopy than outside.

Though Charreau and Vidal (1965) report negative effects on pod yields in groundnut associated with better hay production, most authors agree on the positive effects of *F. albida* on crop yields. Other trees, *Parkia biglobosa* (Jack.) Beuth. (néré) or *Butyrospermum paradoxum* (Gaertn. F.) Hepper (karité) have also positive effects on soil characteristics, but yields of crops grown under their canopy are depressed compared to the outside (Kessler and Boni, 1991). *F. albida* has the advantage of dropping its leaves at the beginning of the rainy season and light interception is much lower by its' canopy than measured from other tree canopies. Soil surface temperature is nevertheless much lower under the tree (35°C) than outside (45°C) after the first rain-storm (ICRISAT, 1991). Given the problems with high temperatures explained earlier in the beginning of the rainy season, this is a finding that should find applications for crop diversification under the tree.

Preliminary trials at ISC show that the benefit of lower soil temperatures combined with improved soil fertility under *F. albida* might allow the production crops such as sorghum, cotton and maize, which are less tolerant to heat than millet (Personal communication, J.H. Williams, ICRISAT Sahelian Center, Niamey, Niger).

*Mixed tree, grass, crop systems*: As mentioned earlier, wind erosion is a major problem in the SSZ. A trial carried out at the ICRISAT Sahelian Center from 1986 to 1989 has shown that borders made of *Andropogon gayanus* Kunth were effective in reducing wind speed and erosion and in protecting the millet particularly at the beginning of the rainy season. Strips 10 m wide had trapped in a three year period more than 2000 t ha\(^{-1}\) of sand (Renard and Vandenbergeldt, 1990).

Farmers in the region are keeping un-weeded strips between their fields to delimit them. Those narrow strips of weeds trap sand and behave much like *Andropogon* strips; but they do not produce much dry matter and the farmers do not benefit from them. These strips are well visible on aerial photographs (Mietton, 1986), since their elevation compared to the field level is higher.

An analysis of aerial photographs of the Sadoré region (Niger) made in 1981 revealed that for an area of 4.5 km\(^2\), the total length of the un-weeded strips was about 45 km (Renard and Vandenbergeldt, 1990). If the farmers were planting these strips with *Andropogon*, they would benefit from the wind protection and make profit since that grass has a value on the market. Strips planted in single rows (1000 pl km\(^{-1}\)) produce about 1.5 t km\(^{-1}\) of forage (3 cuts year\(^{-1}\)) or straw (used for making mats); the same number of plants planted in alternated double rows produce about 2 t km\(^{-1}\) of forage and straw.

In an on-farm project started in collaboration with a development agency in Niger, farmers on their own choice, decided to use *Andropogon, Bauhinia rufescens*, *A. senegal*, and *F. albida* for improving these non-weeded strips. This ASP system takes into account traditional field limits and makes use of traditional plants.

**Rotations**

From the standpoint of efficient resource use, it is recognized that rotation of a cereal with legume offers several advantages. The benefits of the cereal-legume rotation are well documented for temperate
countries, though interest has declined with the introduction of fertilizers, and chemicals to control pests and diseases. The succession or rotation of crops can contribute particularly in the SAT of West Africa (Piciri, 1989) to:

- a better use of nutrients by the succeeding crops,
- a better equilibrium of soil biological activity,
- a reduction of losses due to leaching and of acidity,
- a better management of mineral and organic resources.

A long term experiment initiated in 1986 at ISC for testing 13 different combinations of inputs into an improved production technology for millet proved the pearl millet-cowpea rotation, plus application of P fertilizers, as the most suitable packages to recommend to farmers (ICRISAT annual report 1989, pp. 233-235). Agronomic results showed that the improved system gave consistently higher yields than the traditional system (Fig. 11). From 1986, grain production in the improved systems (P application-rotation legume cereal) showed a 43% increase in a bad year (1987) and a 252% increase in a good year (1988) over the traditional pearl millet/cowpea system.

Results over the five year period show also that with time yearly grain production of the traditional system decreased while the improved system was quite stable. On an average, the traditional system gave a grain yield of 188 kg ha⁻¹ year⁻¹ and the improved system, 498 kg ha⁻¹ year⁻¹.

Hay yields of the rotation system were also much higher (Fig. 11) and in a year like 1990, which was characterized by low rainfall (400 mm) and the occurrence of a dry period at the flowering stage, grain production was more affected than vegetative production, but to a lesser extent in the rotation system than in the continuous system. The adoption of these low input systems which give sustainable production is clearly justified in the SSZ where farmers can rarely afford fertilizers and chemicals.

Integrated use of manures and a limited quantity of fertilizer:

Several studies in the past showed that lack of phosphorus constitutes a major constraint to crop growth in the SSZ (Hauck, 1966; Pichot and Roche, 1972; Jones and Wild, 1975). Results of studies conducted at ISC by the International Fertilizer Development Center (IFDC) showed that application of as little as 20 kg ha⁻¹ of P₂O₅ doubled millet yields. Klaij and Hoogmoed (1987) explained, fertilizer application also helps in ensuring better plant stand. They showed that in plots receiving fertilizer, 74% of the hills survived as against 43% in the control plots.

At locations such as Sadore with a short growing season, efficient water use holds the key to increased yields and yield stability. An important consequence of the use of fertilizer is increased water use efficiency. Early, vigorous growth results in a larger ground cover early in the season. This reduces to some extent the proportion of water that would be lost through soil evaporation, thus helping in an effective and efficient use of rainfall (Sivakumar et al. 1990).

Recent research results show that the integrated use of fertilizers and organic manures help increase crop yields while improving the chemical and physical characteristics of soils. Small farmers in dryland farming systems are more risk averse and freely substitute organic manures for fertilizers (Lipton, 1978).

Use of crop residues

On the poor sandy soils with low fertility in the SSZ, leaving crop residues in the field after harvest benefits crop growth by improving soil physical properties and by adding plant nutrients. Results from ISC (Batio et al. 1987) showed that crop residues help reduce the aluminum and hydrogen saturation of the exchange complex, a major problem on the sandy soils. Millet in the SSZ is traditionally grown in wide rows. Recent investigations at ISC, in collaboration with the Institute of Hydrology (Wallace et al. 1988), showed that water losses in such a system through soil evaporation could be a significant component of the total evapotranspiration (ET). One of the effective means of reducing evaporative losses is through the use of mulching or crop residues. In addition to soil and water conservation, crop residues also regulate soil temperatures, that are usually high in the beginning of the growing season. Use of crop residues could decrease sur-
Figure 11. Pearl millet grain and straw yields in three cropping systems during the 1986-90 growing seasons at ISC, Sadore, Niger.
face soil temperatures by as much as 5-10°C (Lal, 1987).

Protecting the soil surface through the use of crop residues could also help control wind erosion. Distributing the crop residue uniformly on the surface could provide surface cover sufficient enough to reduce wind erosion. Recent research at ISCI suggests that use of millet residues of 1-2 t/ha helped reduce the sand blasting effects and improve the millet establishment and growth.

Cereal stovers and weeds remaining after grain harvest are generally grazed by livestock. Animals often have open access to crop residues. In highly populated areas, however, farmers claim ownership to crop residues and all stovers may be harvested and stored for feeding. Residues from the grain legumes such as groundnut and cowpea are often sold and/or stored as hays for feeding to select animals. In addition to animal feed, cereal stovers are also used as building materials, fuel etc.

The importance of crop residues to animals' diet depends on livestock and cropping densities and the availability of alternative higher quality forages. Crop residue grazing is more important in semi-arid areas than in the more humid zones of West Africa (Table 11). Animals spend 50 to 80% of total grazing time on crop residues during the 2 to 3 months following grain harvest. By selecting the most nutritious components of cereal stovers and weeds (Powell and Saleem, 1986) animals obtain a higher quality diet than from natural pasture during this time of year.

**Table 11.** Contribution of crop residues to annual and seasonal feed intake of ruminant livestock in West Africa (Adapted from Sandford, 1990).

<table>
<thead>
<tr>
<th>Species, system, zone</th>
<th>Feed intake&lt;sup&gt;a&lt;/sup&gt; derived from crop residues</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Year as a whole</td>
</tr>
<tr>
<td><strong>Cattle</strong></td>
<td></td>
</tr>
<tr>
<td>Agro-pastoral herd (semi-arid Mali)</td>
<td>43</td>
</tr>
<tr>
<td>Millet-based agro-pastoral system</td>
<td></td>
</tr>
<tr>
<td>Semi-arid Mali</td>
<td>16</td>
</tr>
<tr>
<td>Sub-humid Nigeria</td>
<td>20</td>
</tr>
<tr>
<td>Semi-arid Nigeria</td>
<td>NA</td>
</tr>
<tr>
<td>Sub-humid Nigeria</td>
<td>13</td>
</tr>
<tr>
<td>Farming area</td>
<td>7</td>
</tr>
<tr>
<td>Grazing area</td>
<td></td>
</tr>
<tr>
<td><strong>Sheep</strong></td>
<td></td>
</tr>
<tr>
<td>Millet-based agropastoral system (semi-arid Mali)</td>
<td>7</td>
</tr>
<tr>
<td><strong>Goats</strong></td>
<td></td>
</tr>
<tr>
<td>Millet-based agropastoral system (semi-arid Mali)</td>
<td>2</td>
</tr>
</tbody>
</table>

<sup>a</sup> Intake assumed to be proportional to grazing time

<sup>b</sup> NA - Not available
The quantities of crop residues produced and, therefore, the number of animals able to be fed during the dry season can vary widely in semi-arid areas (Fig. 12). During years of poor rainfall and crop residue production, the dry season carrying capacity of the semi-arid zone can be greatly reduced. As a result, more animals move to the humid southern areas in search of grazing. Animals also have to leave the zone earlier in the dry season than during years of greater residue production. The most difficult time for livestock feeding is the beginning of the rainy season.

![Graph showing crop residue production](image)

**Figure 12.** Theoretical production of crop residues for 15 years in Senegal (Adapted from Faye, 1986).

**Future Perspectives and Conclusions**

The steady increase in human populations and periodic drought in semi-arid Africa have caused food shortages, put stress on the resource base and has jeopardized the long term sustainability of these agricultural production systems. Development of sustainable food production strategies in the Sudano-Sahelian zone requires a more complete understanding of the limitations of the ecosystem and of the inter relationships between the crops, trees and livestock. Proper incorporation of agroclimatic considerations in the development of improved agro-silvo-pastoral systems requires a much longer time frame than has been used in the past. Climate and soil are the most important factors determining the sustainability of ASP systems and more emphasis should be placed on understanding their potential and limitations and determining the impact of sustained use of a given ASP system on the resource base.

Technological options for ASP systems in the SSZ should be based on both multiple uses and long term maintenance of soil productivity and quality. Browse types that provide food, fodder, wood, soil amendments, and controls to soil erosion can enhance the sustainability of mixed farming systems. The integration of appropriate herbaceous forage legumes with cereal production and fallow systems can provide improve forages for animals and be more effective than natural vegetation in restoring soil productivity. Improved crop and animal management strategies are also required to alleviate the competition between animals and soil management for crop residues. The economic, ecologic, and social stability and sustainability of semi-arid farming systems depends upon technologies that mutually benefit both crop and livestock production.

Given the complexity of the ASP systems in the SSZ, the task of "matching" an improved system with the physical environment is not easy. It is imperative that more emphasis should be placed on multidisciplinary 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.
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IMPORTANCIA ECONOMICA DE LA INFORMACION AGROMETEOROLÓGICA

por

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IMPORTANCIA ECONOMICA DE LA INFORMACION AGROMETEOROLÓGICA OPERACIONAL

Dr. Jose F. Villalpando

INTRODUCCION

Sin duda una de las aplicaciones más importantes de la meteorología es en la agricultura. La aplicación de la meteorología en la agricultura es a través de la información agrometeorológica, la cual resulta de la interrelación de los datos agrometeorológicos y de los datos biológicos colectados de plantas y animales. El análisis conjunto de estos dos componentes y su interpretación constituye la información agrometeorológica con la cual es posible evaluar el impacto del tiempo y del clima sobre la producción de cultivos. La información agrometeorológica por tanto, es la fuente de información indispensable para la toma de decisiones a corto y mediano plazo en las actividades operativas de la agricultura.

Algunas actividades agrícolas donde la información agrometeorológica operacional resulta de gran beneficio económico, son las siguientes: 1) Reducción y oportunidad de aplicación de pesticidas en los cultivos, 2) Optimización del uso del agua de riego en la agricultura, 3) Dosificación y oportunidad de aplicación de fertilizantes en los cultivos, 4) Protección de cultivos contra las heladas, 5) Selección de variedades de cultivos agrícolas, 6) Determinación de fechas de siembra en cultivos de secano, 7) Uso de la maquinaria agrícola, 8) Etc.

La toma de decisiones sobre las actividades agrícolas antes mencionadas, las cuales realiza diariamente o cada semana, el agricultor o el agrónomo, pueden beneficiarse con la aplicación oportuna y correcta de información agrometeorológica. Sin embargo, persiste el problema de como evaluar de manera objetiva tales beneficios económicos en la agricultura. Actualmente no existe suficiente información publicada (WMO Technical Note No. 192), que permita ser utilizada para demostrar en forma cuantitativa los beneficios económicos, que la información agrometeorológica puede ofrecer a los usuarios agrícolas. Por lo tanto, ésta debería ser una de las actividades a desarrollar e impulsar en los departamentos de agrometeorología de los Servicios Meteorológicos, de los Institutos de Investigación Agrícola, así como de las Facultades de Agricultura de las Universidades.

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No obstante las limitaciones antes mencionadas, en este escrito se proponen algunas formas, y criterios económicos que eventualmente podrían ser utilizadas para evaluar los beneficios económicos derivados de la aplicación de la información agrometeorológica en la agricultura. Además, se presentan cuatro ejemplos, para ilustrar algunos de los criterios para evaluar el beneficio económico de la información agrometeorológica. Finalmente se presentan algunas conclusiones y recomendaciones.

FORMAS, FACTORES Y CRITERIOS DE EVALUACION

1. Formas de Evaluación

Entre las formas para evaluar los beneficios económicos de la aplicación de la información agrometeorológica operacional, se mencionan las siguientes:

1) Evaluación al nivel de una región agrícola completa, la cual podría incluir cultivos diversos, como frutales, hortalizas y otros. La superficie de la región seleccionada podría cubrir varios miles de hectáreas. La evaluación de los beneficios económicos de la información agrometeorológica, podría llevarse a cabo mediante el muestreo de predios agrícolas, para conocer si aplicaron o no la información emitida por el Servicio Meteorológico, y desde luego, los beneficios obtenidos de dicha información.

2) Evaluación al nivel de un predio agrícola en particular. Aquí la evaluación del beneficio económico de la información agrometeorológica se puede realizar con más detalle, que en el caso de una región agrícola completa. A este nivel, el uso de estaciones agrometeorológicas automáticas instaladas en los campos de cultivo, proporcionarían la mayor parte de la información necesaria para el control de plagas y enfermedades, el uso del agua de riego, el pronóstico de heladas del tipo de pérdida de radiación, etc.

3) Otra forma de evaluación, por ejemplo en el caso del daño por heladas a los cultivos, consiste en comparar los daños causados por heladas en inviernos donde se proporcionaron avisos meteorológicos de alerta de heladas, contra aquellos inviernos donde tales avisos no fueron proporcionados a los usuarios, y también ocurrieron heladas.
2. Factores de Evaluación

Algunos de los factores de evaluación, con los cuales se puede estimar el beneficio económico de la aplicación de la información agrometeorológica, se listan a continuación:

1) Reducción de costos, por menor número de aplicaciones de pesticidas a los cultivos, 

2) Reducción de costos de cultivo, por menor uso de maquinaria agrícola, menor uso de combustibles, reducción de la mano de obra, 

3) Mejor calidad de los productos agrícolas, 

4) Incremento en el rendimiento de los cultivos por unidad de superficie, 

5) Ampliación de la superficie de riego, debida a la optimización del uso del agua para la agricultura, 

6) Reducción del deterioro del medio ambiente por uso excesivo o mal uso de pesticidas, fertilizantes, agua para la irrigación de cultivos, etc., 

3. Criterios de Evaluación

Por otra parte, algunos criterios que podrían ser utilizados para evaluar el beneficio económico por la aplicación de la información agrometeorológica, son los siguientes:

1) Utilidad neta por hectárea, como resultado de la diferencia entre la ganancia adicional y los costos que implica el uso de información agrometeorológica, 

2) Ganancia adicional por ahorro en el uso de insumos agrícolas tales como pesticidas, fertilizantes, agua de riego, combustibles utilizados para el combate de heladas, etc., a nivel de una región, o al nivel del predio de un agricultor, 

3) Ganancia adicional por el uso de información agrometeorológica oportuna, que incremente la producción y calidad de los productos agrícolas, 

3) Relación beneficio/costo
EJEMPLOS DE BENEFICIOS ECONOMICOS DE LA APLICACION DE LA INFORMACION AGROMETEOROLÓGICA OPERACIONAL

Se presentan cuatro ejemplos donde se muestran los beneficios económicos potenciales de la información agrometeorológica: 1) Reducción y oportunidad de aplicación de pesticidas en los cultivos, 2) Optimización del uso del agua de riego, 3) Dosificación y oportunidad de aplicación de los fertilizantes, y 4) Protección de los cultivos contra las heladas.

Ejemplo 1. Reducción y oportunidad de aplicación de pesticidas en los cultivos

En el Estado de Colima, México, la producción de melones del tipo cantaloupe actualmente se realiza en una superficie de aproximadamente 3,000 has. La producción de esta fruta está orientada principalmente hacia la exportación, principalmente a los Estados Unidos de América. Para proteger al cultivo de melón contra eventuales ataques de plagas y enfermedades, los agricultores de esta región hacen uso de pesticidas, siguiendo el esquema convencional denominado: "Seguro del Cultivo". Bajo este esquema, los agricultores hacen una aplicación de insecticida/fungicida, cada semana o cada 10 días, en cultivos de alto valor económico como tomate, melones, fresa, papa, etc., independientemente de las condiciones meteorológicas que se presenten es estos cultivos.

En cambio, bajo un esquema de uso de información agrometeorológica, para tomar la decisión sobre si aplicar o no el pesticida, sería el siguiente: si las condiciones meteorológicas recién pasadas y de las próximas horas no son favorables para el desarrollo de un determinado patógeno, entonces no será necesario hacer una aplicación de fungicida. Caso contrario, la aplicación del fungicida será necesaria. La herramienta necesaria para tomar la decisión es un modelo de pronóstico para la enfermedad en cuestión (WMO Nota Técnica No. 192).

A continuación se presenta el beneficio económico debido a la reducción de solamente una aplicación de fungicida para combatir la enfermedad denominada "cencilla" (Sphaeroteca fulginea) que ataca a las plantaciones de melón. El beneficio económico se calcula tanto a nivel de toda la zona de producción de 3,000 has., como de un agricultor individual con una superficie sembrada de 60 has.
Datos:
- Superficie sembrada de melón: 3,000 has.
- Costo de una aplicación de fungicida, aprox. U.S. $ 50.00
- Costo de una estación agrometeorológica automática y un equipo de cómputo, aproximadamente U.S. 20,000.00
- Costo de desarrollo y adecuación local del modelo de pronóstico para la cenicilla del melón, $ 15,000.00
- Costo de diseminación de la información agrometeorológica a los usuarios, durante un ciclo agrícola de 6 meses, un técnico, y materiales misceláneos, aprox. U.S. $ 12,000.00

Beneficio económico por la reducción de una aplicación de fungicida:

Nivel región:
Superficie de 3,000 has x U.S. $ 50.00 = U.S. $ 150,000.00
Utilidad bruta: $ 150,000.00
Costos: 47,000.00
Utilidad neta $ 103,000.00
Relación beneficio/costo: 150,000.00/47,000 = 3.19

Nivel productor:
Superficie de 60 has x U.S. $ 50.00 = U.S. $ 3,000.00
Utilidad bruta: $ 3,000.00
Costo Prorrateado: 783.00
Utilidad neta $ 2,217.00 (ingreso adicional)

Ejemplo 2. Dosificación y oportunidad de aplicación de fertilizantes en maíz de secano

En la región de El Bajío, ubicada en la parte centro de México, se siembran alrededor de 100,000 hectáreas de maíz de secano. Una de las decisiones más importantes y de mayor valor económico que tiene que hacer el agricultor cada ciclo agrícola, es aquella de cuánto fertilizante aplicar a sus cultivos. En estas regiones la cantidad de fertilizante y el rendimiento de los cultivos depende en gran medida de la cantidad de lluvia que reciben los terrenos de los agricultores durante la estación de lluvias. Por lo tanto, la decisión del agricultor, acerca de cuánto fertilizante aplicar, dependerá del pronóstico de lluvia estacional
(3-4 meses). Mientras que la decisión de cuándo aplicarlo, depende del contenido de humedad en el suelo, de la fase fenológica del cultivo y del pronóstico de lluvia para las próximas 24-72 horas.

La cantidad óptima de fertilizante a aplicar a los cultivos de secano, como el maíz, puede determinarse mediante una función de producción, donde el rendimiento se puede expresar como una función de la cantidad de lluvia y de la cantidad de fertilizante aplicado (Figura 1). De ahí que, el pronóstico de lluvia estacional resulte ser la información agrometeorológica básica para decidir la cantidad de fertilizante y de esta manera tener una estimación del posible rendimiento de maíz.

**Datos:**

- Superficie sembrada de maíz: 100,000 hectáreas

- Aplicación promedio de fertilizante nitrogenado en la región: 80 Kg/ha

- Rendimiento estimado de maíz, para un pronóstico de lluvia estacional favorable (año húmedo):

<table>
<thead>
<tr>
<th>Estación de lluvias</th>
<th>Nitrógeno Kg/ha</th>
<th>Rendimiento de maíz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Año húmedo (P≥ 500 mm)</td>
<td>120</td>
<td>4.0 Ton/ha</td>
</tr>
<tr>
<td>Promedio (P= 350 mm)</td>
<td>80</td>
<td>3.0 Ton/ha</td>
</tr>
<tr>
<td>Diferencia</td>
<td>40</td>
<td>1.0 Ton/ha</td>
</tr>
</tbody>
</table>

- Valor de 1.0 ton/ha de maíz (en México) = U.S. $ 250.00

- Costo de 40 Kg/ha de Nitrógeno = U.S. $ 20.00

- Costo de la preparación y diseminación de la información agrometeorológica del pronóstico de lluvia estacional, U.S. $ 20,000.00

Considerando que el 10% de los agricultores aplica la información de pronósticos de lluvia estacional en el primer año, y que éstos pronósticos son correctos, se tendría lo siguiente:
Figura 1. - Funciones de rendimiento de maíz simuladas para seis niveles de lluvia (mm) en la región de El Bajío, México (Villalpando, 1981).
Situación para un año húmedo

Incremento en la producción de maíz:

\[ 1.0 \times 10,000 \text{ has} = 10,000 \text{ toneladas adicionales} \]

Valor de la producción:

\[ 10,000 \text{ ton.} \times \text{U.S. } \$ 250.00 = \text{U.S. } \$ 2,500,000 \]

Utilidad neta= Valor de la producción - costos

= \$ 2,500,000 - 220,000
= \$ 2,280,000 adicionales

Relación Beneficio/Costo = 2,500,000/220,000 = 11.36

Ejemplo 3. Optimización del uso del agua de riego en la agricultura de México

En México la superficie agrícola con agua de riego es de aproximadamente 5,000,000 de hectáreas. Se considera que la optimización del uso del agua de riego haciendo uso de información agrometeorológica podría incrementar la superficie de cultivo en un 10%. Es decir, unas 500,000 has adicionales. El beneficio económico estimado sería el siguiente:

Datos:

- Superficie de riego actual aproximada: 5,000,000 has

- Incremento del 10% de la superficie (500,000 has) por el uso eficiente del agua de riego

- Suponiendo el uso de la información agrometeorológica en un 5% por año (20 años en total), cada año se agregarían unas 25,000 has adicionales

- Costo de estaciones agrometeorológicas automáticas instaladas en las zonas de riego (tres por cada 25,000 has) U.S. $ 45,000.00

- Preparación y diseminación de la información

  U.S. $ 30,000.00

Valor de la producción de 25,000 has adicionales/año,

\[ 25,000 \times \text{U.S. } \$ 2,000 = \text{U.S. } \$ 50,000,000 / \text{año} \]

Beneficio neto = 50,000,000 - 75,000 = U.S. $ 49,925,000
Ejemplo 4. Reducción de pérdidas por daño de heladas en frutales caducifolios en Chile

En Chile en 1981 las pérdidas por daño de heladas en frutales ascendieron a U.S. $ 40'000,000.00. El beneficio económico por la emisión de avisos agrometeorológicos y el uso de prácticas de protección contra heladas puede estimarse con el uso de los datos siguientes:

Datos:

- Pérdidas por daño de heladas en frutales en 1981, U.S. $ 40,000,000.00

- Eficiencia del 10 % en el uso de la información del pronóstico de heladas. Es decir, que entre las diferentes prácticas de control se lograra una eficiencia del 10 % en el primer año

Beneficio económico aproximado para el primer año,

U.S. $ 4'000,000.00

CONCLUSIONES Y RECOMENDACIONES

1. La información agrometeorológica operacional tiene un gran valor económico en la toma de decisiones de muchas actividades agrícolas.

2. El beneficio económico derivado de la aplicación de la información agrometeorológica operacional, es posible cuantificarlo, seleccionando los factores y criterios adecuados que permiten evaluar en forma objetiva este beneficio.

3. A través de datos reales, se presentan cuatro ejemplos que muestran el potencial de beneficio económico de la información agrometeorológica.

4. En base a los lineamientos presentados en este artículo, se recomienda a los programas de agrometeorología de los Servicios Meteorológicos Nacionales, los Institutos de Investigación Agrícola y las Universidades Agrícolas, desarrollar estudios de caso, orientados a cuantificar los beneficios económicos de la información agrometeorológica.
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