EVERYBODY COMPLAINS ABOUT CLIMATE...

WHAT CAN AGRICULTURAL SCIENCE AND THE CGIAR DO ABOUT IT?

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1. UNCERTAINTIES IN CLIMATE AND AGRICULTURAL PRODUCTION

This paper examines the links between climate and agriculture[2]: climatic factors like solar energy (radiation) and water are essential to agricultural production; they constitute major environmental resources and the development of technologies for their improved management is one of the roles of agricultural research.

Then we examine the losses brought about in current production systems by the natural and human-induced variability of climate (see Box 1 for definitions), and the now well accepted evidence that climate change is one of the factors which has to be reckoned with, in spite of the uncertainties affecting all change scenarios, or perhaps precisely because of the uncertainties.

A major change in perception that occurred over the recent years is the fact that interactions between atmosphere and agriculture are no longer seen as unidirectional (climate impact), but rather that agriculture also affects global climate as one of the sources of greenhouse gases and a sink for CO_2. The feed-backs highlight that agriculture is part of the global environment, and that the issue of sustainable agriculture, due to its links with population and socio-economic considerations is thus a relevant topic also beyond the agricultural community, as was highlighted in the recent Kyoto protocol.

Climate change impacts can be understood only in the light of current atmosphere-plant-soil interactions, unless unusual or unexpected combinations of factors should develop, where “unusual” refers to changing averages, the frequency of occurrence of factors, their combination and, possibly their nature as in the case of CO_2 and UV-B, two factors which had until recently been regarded as “constants”. A better understanding of current climate-agriculture interactions remains thus the key to a better understanding of future conditions and impacts.

Large uncertainties are associated with the dynamics of agriculture, as driven by such inter-related factors as population growth (Gommes, 1992), land degradation, international markets, changing diets linked with improving standards of living or other mechanisms,

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[2] The FAO usage of the term includes crop and animal husbandry, forestry and fisheries.

technology and management, etc. Implications for future food security (Bohle et al., 1994; Chen, 1994; EC, 1997) and biodiversity (Emanuel et al., 1985) are thus complex.

Our ignorance about future climate, associated with our poor ability to foresee the evolution of world agriculture beyond ten or twenty years are thus a central issue to be considered: we still do not have the adequate tools to bridge the gaps between spatial and temporal scales, and there is an urgent need to reassess some research priorities in the CGIAR (Fresco and Kroonenberg, 1992).

We insist on areas of uncertainty where additional research is required, as well as some considerations deriving from the ongoing international climate discussions.

Box 1 : weather and climate definitions

Weather describes the condition of the atmosphere at a well defined location and at a given time. Climate, on the other hand, refers to average conditions at the same location. Obviously, adjacent areas tend to undergo similar climate conditions and, therefore, climate can be seen as the average atmospheric conditions over sometimes large areas. It is stressed that variability is as much a characteristic of climate as the averages.

Amazingly, there does not appear to be a generally agreed definition of the terms of "variability" and "change", for which Maunder (1994) lists different acceptations. He mentions that *the term climate change is also often used in the more restricted sense to denote a "significant" change (that is, a change which has important economic, environmental and/or social effects) in the mean values of a meteorological element (...) during the course of a certain period of time, where the means are generally taken over periods of a decade or more (Maunder, 1994, p. 39)*. Maunder defines "fluctuations" as *changes in the statistical distributions used to describe climate states* (p. 45). As to "variability", one of the definitions proposed is *deviations of climate statistics over a given period of time (such as month, season, year) from the long-term statistic*, i.e. the departure from the long-term average (p. 56). As with micro-climate, there appears to be a difference in the use of the terms by statistical climatologists and ecologists!

The present paper uses "variability" to describe the statistical noise about the average at time scales from days to years, and "change" in the same sense as Maunder, i.e. long-term changes in the average.

2. CLIMATE AS "RESOURCE"

This section presents the view that there is a lot to be gained from looking at climate not only as a hazard, but also as a "resource". Resources must be known, assessed in quantitative terms and properly managed if they are to be used sustainably, and climate is no exception.

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

2.1 The climate complex

Climate constitutes a "complex", i.e. set variables which behave coherently, essentially as a result of atmospheric physics and dynamics (Sombroek and Gommes, 1996). For instance, rainfall tends to cool the atmosphere because water evaporation absorbs heat; cloudy days are characterised by a low daily thermal amplitude (difference between day and night temperature), relatively high air moisture and low evaporation, etc. In addition, the statistical properties of climate derived from long-term observations ensure that the usual range of variation of the "complex" is known.

Notwithstanding the difficulties of short-term weather forecasts proper, weather thus behaves rather coherently, and this constitutes an essential piece of knowledge which can be applied to improve the output of agricultural systems in terms of amounts and regularity.

The "complex" is also at the basis of agroecological zones (AEZ) interpreted as areas of relative climate stability, associated with typical soils and spectrum of characteristic plants and animals constituting the production system. FAO has been constantly developing the AEZ concept as a basic planning tool in agriculture starting in the late seventies (FAO 1978a, 1978b, 1980, 1981).

The section below lists the climate variables which are most relevant for plant growth (development) and production. They can all be subdivided into a "normal" or physiological range with a largely predictable effect on plants and animals. The "extreme" range, by definition, covers unusually low or high values. The extreme effects on living organisms are far less predictable, for several reasons:

- they may mechanically damage plants and harm animals;
- their occurrence is rare and therefore less data are available for fine-tuning impact models;
- experimental stations tend to discontinue observations after the occurrence of extreme conditions, thereby further reducing the observation base that would be required for impact assessments.

2.2 The climate resources

2.2.1 Solar energy and light

The sun is the primary source of almost all energy stored in organisms in the form of biomass chemical bonds, starting with plant photosynthesis. The maximum amount of solar energy available as light depends essentially on astronomic factors (Hupfer, 1991), where variations of the solar constant (sunspot cycle of about 11 years), the annual and diurnal cycles play the most relevant role. Longer cycles (11,000 to 110,000 years) are associated with the orbit of the earth).

In general, clouds and various aerosol (sulphates, dust, etc.) can reduce the amount of energy that reaches the ground. Aerosol, including anthropogenic sulphates, have recently been shown to play a significant part in the energy balance of the earth. Dust is often of volcanic origin (e.g. eruption of Mount Pinatubo in 1991) and therefore a-periodic, but the increasing frequency of dry haze in West Africa seem to indicate a link with land degradation.

Finally, clouds constitute one of the major uncertainties in the current climate change scenarios, as a small increase of the planetary albedo could result in global cooling instead of global warming.

Light also plays an important qualitative role by triggering the photoperiodic response of crops[3] and by influencing the reproductive cycle of animals.

2.2.2 Water

While solar energy sets the maximum value of the energy available for plant growth, water determines to what extent the energy can be used. In fact, plants "pay" for the energy they absorb by transpiring water, and similarly water plays an important part in the thermoregulation of animals[4]. The rather direct and almost linear link between actual water consumption and plant production has been very well documented (Chang, 1974; Begun et al, 1991, etc.) and the interactions between transpiration and assimilation have been at the core of plant models from the early stages (de Wit et al.1978; van Keulen and Wolf, 1986).

This simple fact is often overlooked in semi-arid areas: all factors which increase biomass (like the introduction of HYV or the use of fertiliser) also increase water consumption, sometimes resulting in agricultural drought under climatically rather average conditions.

Rainfall still constitutes the main source of water, and many techniques exist to improve water availability through water harvesting, irrigation, flood recession, cropping and grazing, or breeding, for instance for stronger root development. Less conventional sources like dew and fog may be resorted to locally (Acosta-Baladon, 1996).

Finally, air and soil moisture and water bodies play a very direct role in creating conditions favourable for the development of many pests, diseases, pathogens and their vectors (e.g. egg pod deposition and hatching conditions in desert locusts, liver fluke distribution, etc.)

2.2.3 Wind

At the micro-scale, wind has a less direct effect on plants than solar energy and water. It plays a part in mixing air and homogenising temperatures in canopies, thereby ensuring the continued exchange of CO_2 and water between plants and the atmosphere. It also

[3] E.g. the length of the day provides the signal for flower development in some crops, such as some varieties of millet or rice

[4] Disorders of thermal regulation are at the root of many of many diseases and a cause of poor growth and production (meat, milk, eggs).

contributes to the dissemination of pollen in wind-pollinated plants and the movement of migratory pests, but wind is more often associated with negative effects, including excessive desiccation, physical damage to crops, either directly or through abrasion by transported particles.

2.2.4 Heat and temperature

Temperature is the yardstick used to measure heat, i.e. the energy stored in the thermal motion of particles. Most chemical processes, and therefore biological processes as well, are temperature dependent. Within the limits of the normal physiological range, the speed of biochemical reaction approximately doubles for a temperature increase of 10°C. It is worth noting that the reactions of assimilation (photosynthesis) are globally less dependent on temperature than, for instance, respiration.

In general, higher temperatures are thus associated with higher productivity and shorter biological cycles. This is amply illustrated by the high biomass turnover of the tropical rainforests (where biomass production is paralleled by high rates of decomposition of plant residues), or the short cycles of pests and diseases in warmer climates (for instance, the length of the development of eggs of *Diabrotica virgifera*, a common maize pest in temperate areas varies from 160 to just 14 as a function of temperature; Schaafsma et al., 1991).

Many qualitative thresholds are temperature dependent (for instance vernalization of winter crops, tuberisation, break of the diapause in insects).

Finally, air and soil temperatures play a major role in the development of growth of cold-blooded animals (earthworms, fish, etc.).

2.3 Production potential and biodiversity

The energy balance and the water balance of crops are interrelated through crop evapotranspiration. Evapotranspiration is a central concept in the determination of the potential biomass, i.e. the maximum quantity of plant biomass which can be accumulated under a given climate, assuming no interference of limiting factors such as poor soils, water stress or pest attacks. Next to quantity, the timing (calendar) of the production is mostly conditioned by limiting water availability in the warm climates, and by temperatures in the temperate ones.

At the global scale, very direct links can be established between the main characteristics of climate and biological productivity[5] (Lieth, 1972, 1973 and 1975; Uchijima and Seino, 1985; White et al., 1992). Interestingly, curves very similar to the theoretical biomass

[5] Note that this "global" primary production is different from the now classical approach of Monteith (Kumar and Monteith, 1981) which aims at determining the potential biomass at a given location for a given plant. The values derived from the equations of Monteith are typically several times larger than the biomass of natural vegetation or crops.

curves can be obtained with actual crops, as exemplified below with African crop yields (Figure 1) as a function of National Rainfall Indices[6].

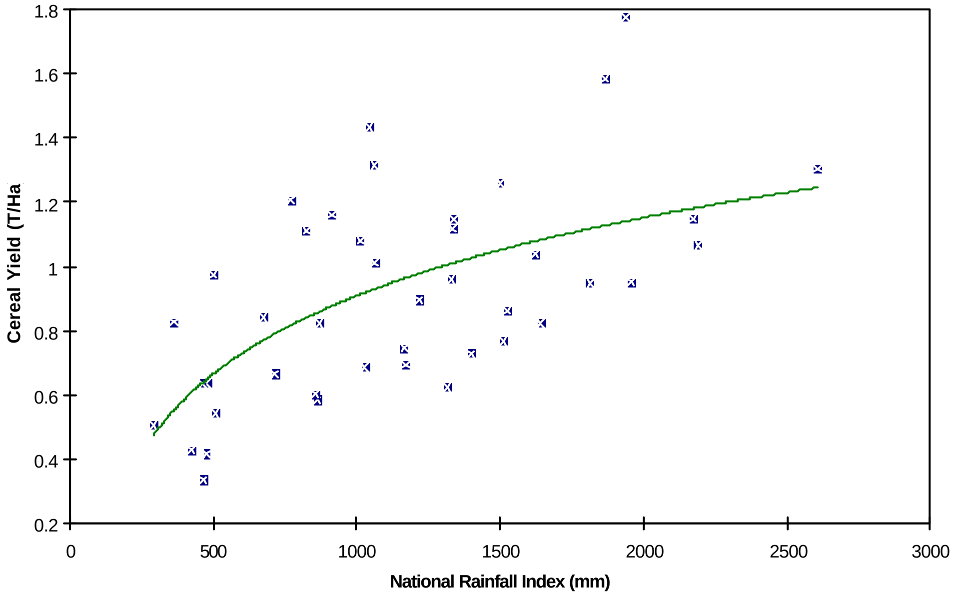

Figure 1 : average 1961-94 aggregated cereal yields in Africa as a function of National Rainfall Index

Climate resources also directly affect biodiversity of land and marine ecosystems (WCMC, 1992; Solbrig, 1992, and several chapters in Solbrig, 1992: Laserre, 1992; MacDonald 1992; Solbrig et al. 1992; Tilman et al., 1997).

[6] The National Rainfall Index (NRI) was introduced to provide a simple tool to compare rainfall conditions, at the national level, between countries and years. For a given year, NRI is the area-wide average of station rainfall, weighted by the long-term average: high rainfall areas receive a higher weight than semi-arid areas, thereby providing an agricultural bias (Gommes and Petrassi, 1994). Note that the water use efficiencies which can be derived from national statistics differ from those of well managed crops by up to two orders of magnitude.

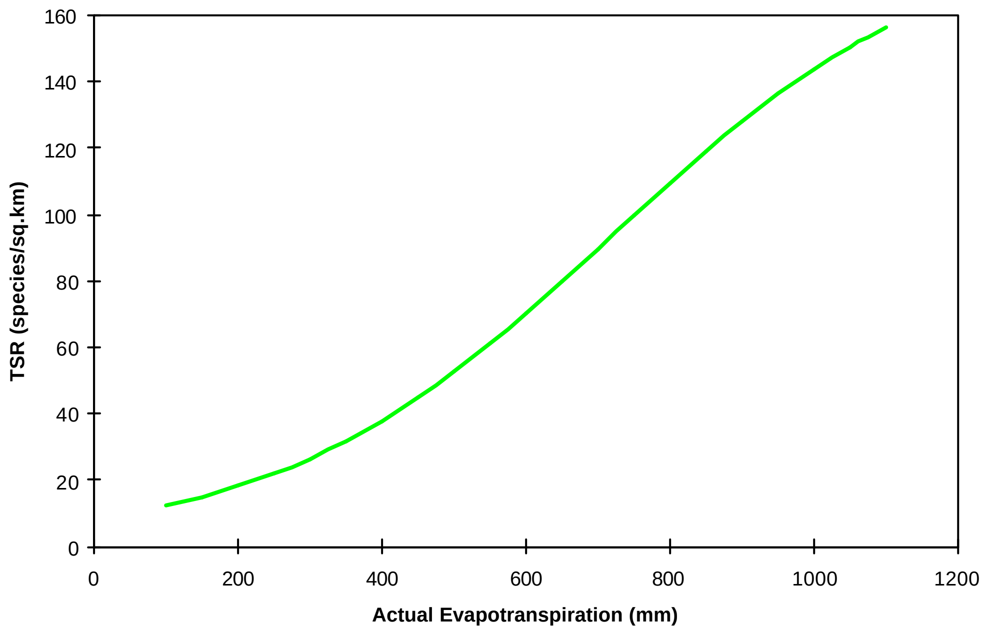

Figure 2: Tree species richness (TSR, number of species per square km) as a function of actual evapotranspiration in the USA, Canada, UK and Ireland (after Currie and Paquin, 1987).

Moore (1987) indicates that the biodiversity relates directly to the number of organisms which can make a living out of available resources, which in turn may be dependent on the extent of these resources, the limitations of the physical environment, the way in which resources present themselves for exploitation (habitat heterogeneity), the number of species geographically available, site accessibility, etc. He further states that forest richness is mainly the product of the resource base - water, warmth and solar energy - : the total available energy is partitioned among species and limits species richness, as shown, for instance, for temperate forests by Currie and Paquin (1987) in their study on Tree Species Richness (TSR) in the USA, Canada, UK and Ireland (figure 2).

There are many examples of species and ecosystems with narrow ecological amplitudes, the occurrence of which is directly associated with climatic conditions. For instance, on the east coast of the US, the spawning of shad (*Alosa sapidissima*) peaks at 15°C. Temperature changes could reduce number of repeat spawners and reduce success (Ray, McCormick-Ray and Potter, 1993); mean annual temperature of 11°C appears to be the upper temperature for the formation of ombrotrophic bogs in NW Europe (Schouten, Streefkerk and van der Molen, 1992); prolonged summer chilling (less than 4°C) is lethal to the small white butterfly (*Pieris brassicae*) and eggs deposited at temperatures above 33°C are infertile[7] (Dennis, 1993).

Most effects described above apply to crops, forest plants, rangeland, farm animals, fish, etc. As well as and to their competitors, i.e. weeds, pests, fungal and microbial pathogens. Some are remarkably efficient at utilising the available climatic resources. Their short cycles and easy dissemination by wind and rain splash are an added advantage.

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[7] Incidentally, *Pieris brassicae* is also a pest affecting many plants of the *Brassicacae* (cabbage family) and its impact under changed climate conditions may differ from current patterns.

Next to the direct effects described above, the following can also be included under indirect effects of climate:

- bush and forest fires;
- the development of pests, including migratory pests, that attack field crops, forests, livestock and other farm animals;
- the action of climate on infrastructure;
- the general well-being and health of people (McMichael et al., 1996) and animals, including draught animals;
- the trafficability and effect on farm operations and their timing.

3. CLIMATE VARIABILITY AND CHANGE : CLIMATE AS HAZARD

We have so far covered essentially the positive aspects of weather on production. The main hazard associated with weather and climate is random variations[8], which border on unpredictability at all time scales exceeding a couple of days. The reduction of the uncertainty at the scale of weeks to seasons (seasonal forecasts) would constitute a major improvement of food security.

While it is recognised that some extreme climatic factors can provoke massive destruction of infrastructure, crops, livestock, fishing gear, etc. and the loss of human life, far more losses are associated with the chronic and inconspicuous effects of climate variability, like droughts, pest attacks, biodegradation of agricultural materials, products, including agricultural structures. The chronic impact of short-term climate variations (up to several years) is difficult to assess in quantitative terms. After describing some features of climate variability, the sections below conclude that about 10 to 20% of national production can be lost annually due to climate variability, and that the figure can reach 100% in extreme cases in small semi-arid developing countries.

According to Oerke et al. (1994), production losses due to pests, diseases and weeds amount to 15%, 14% and 13%, respectively, on average for the main cereals and potatoes, in the absence of control measures. This refers to actual conditions. When compared with potential yields, the loss reduction is roughly 70% equally distributed between pests, diseases and weeds. Needless to say, pests attacks and diseases are often indirectly conditioned by climatic conditions.

3.1 Characteristics of variability

Variability has a structure, i.e. it exhibits transient behaviours which can be analysed statistically and sometimes used for planning. Without entering into detail, the following examples can be mentioned:

- trends, like the downward trend that affected Sahelian rainfall between the early 1960s and 1984;

[8] We stress the fact that it is the uncertainties that constitute a hazard. Many variations (like the alternation of low and high temperatures during night and day, or the alternation of dry and wet seasons) also have beneficial aspects.

- persistence, i.e. the tendency for weather types to occur in clusters: runs of dry and wet days, or runs of dry and wet years etc.;
- pseudo-cycles, often a direct result of persistence. A main characteristic of "cycles" seems to be that they collapse before they reach statistical significance;
- extremes follow well known patterns for each of the climate variables.

Several of the listed characteristics have marked effects on agricultural production and food security. For instance, one of the consequences of persistence is that a "bad" year is more likely to be followed by another "bad" year than by a "good" or "average" year. To some extent, when clusters have a relatively predictable behaviour, this information can be used in agricultural planning.

3.2 Atmospheric pollution

Air pollutants affect life in the immediate surrounding of point sources. Some forms of pollution, like acid rain and ozone, are however known to have significant effects on forest and crop yields over wide areas, particularly in humid climates which improve contact between pollutants and plant surfaces.

Tropospheric ozone is singled out because it derives for about half from photochemical reactions involving nitrogen oxides and methane, and because of its effect on crops, particularly legumes.

3.3 Direct and indirect factors and complex interactions

The potential direct negative effects of most climate elements on crops, natural vegetation and forest, and farm animals are well known. They affect all spatial scales from plant organ to the region, through various mechanisms.

For instance, high temperatures increase water stress in all organisms; they induce sterility in certain crops, lead to poor vernalization and increase winter survival of pests in temperate countries. High night-time temperatures are associated with a production loss due to increased respiration loss. In extreme cases, low temperatures can mechanically destroy cell structure (frost); they also contribute to plant desiccation and cause slow growth, particularly during cold waves, etc.

The direct impact of negative climate factors on agriculture, even the spectacular ones (hail, cyclones) is mostly very limited spatially: the main risks lie more with indirect impacts such as conditions favourable for pest and disease outbreaks, fires, etc.

The relative importance of fires and some other factors is illustrated below (Table 1), based on South African plantations data during 1984-85 (Environmental Affairs, 1986), where fires, wind, snow and hail account for half of the area affected by adverse conditions[9]. Drought turned out to be a negligible factor while pests and diseases make up the other half. If the same results are presented by value, a completely different picture emerges: about 83% of the damage is to be ascribed to fire only, followed by rodents (12.7%) and by

[9] The area affected by noteworthy adverse conditions amounts to less than 5% of the total plantation area.

winds (1.9%). In this particular instance, insects and other weather factors played a negligible part.

Table 1: relative share of losses (%) in south African plantations during 1984/85 as a function of their cause (based on data in Environmental Affairs, 1986)

	Area affected	Financial loss
Drought	0.2	Negligible
Fungi and rodents	8.2	12.7
Wind, snow and hail	11.7	1.9
Insects	40.9	1.6
Fire	39.0	82.8
Others	Negligible	1.0

There are many complex interactions where trends affecting non-climate variables eventually lead to a greater vulnerability of production systems to climate variability. Several examples could be given where population growth has lead to the horizontal expansion of agriculture into marginal areas with low water storage capacity: such areas are more prone to agricultural drought as they cannot "buffer out" short dry spells (Gommes, 1992). The problem will now be perceived as "drought" even if climate remained stable. This is one of the components of the recent 1994 Rwandan genocide (Gommes, 1997).

Another related factor is the switch from traditional crops grown with low water requirements (millet/sorghum) towards crops with high moisture requirements (maize) as a result of changing dietary patterns

Long-term effects on production and quality of the diet must also be taken into account when trees or plantation crops suffer damage due, for instance, to violent winds or salinization (due to ocean spray during cyclones, or to other causes).

3.4 From climate variability to agricultural statistics

Climate variability directly and indirectly affects agricultural output (production) through its effects on yields and areas planted. Yields are affected, as indicated, by weather as the main "random" factor, but also by mostly continuous technological trends (including new varieties and management), innovations (including management innovations), agricultural policies (mostly national policies) and extreme factors of various origins.

Variation of areas depend more on economic factors. Areas planted vary according to labour availability, level of mechanisation and expected return (prices). Areas harvested are often strongly linked to environmental conditions, including poor weather during the cycle, damage to infrastructure due to extreme conditions, etc.

Because of the complexity of the dependence of area-wide[10] yields on different factors, and because of the high level of aggregation of agricultural statistics, it is not always easy to show the effect of climate variability[11].

[10] Area-wide refers to yields and production by administrative units, from the village level to the national level, as opposed to a field, where conditions can be assumed to be reasonably homogeneous.

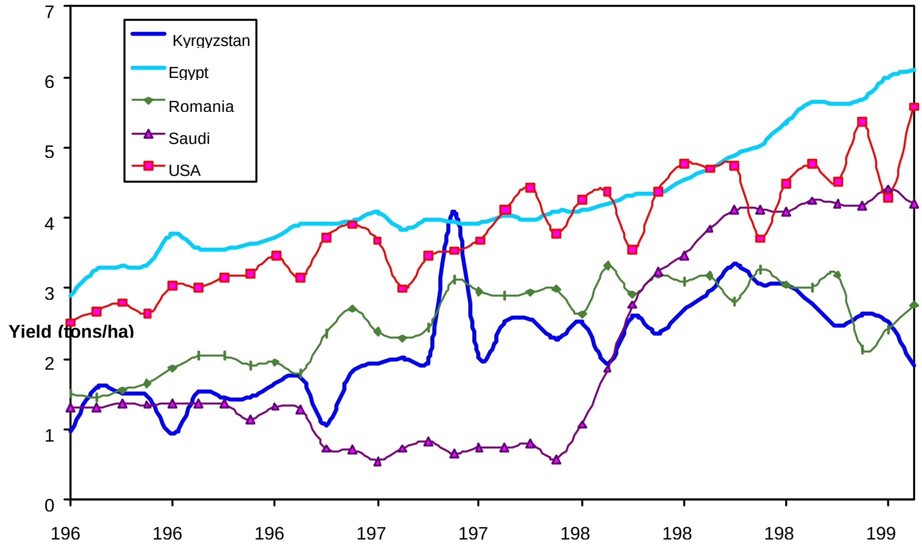

Figure 3 : time series of national cereal yields (all cereals) in five countries between 1961 and 1994 (based on data from FAO 1994).

In order to isolate the effect of environmental conditions from other factors, the first step is to eliminate the trends in the series. This makes sense only when there is no marked trend in the weather, which happens to be the majority of cases. In addition, trends are not always constant and the detection of trend changes constitutes, per se, a rather difficult technical problem. As an example, some recent time series of yields are shown in figure 3. The countries were chosen only to provide examples of the variety of temporal behaviour of yield time series. The only "clean and easy" series is that of the USA, where a meaningful linear trend can be computed. In Egypt, the variability is relatively low (due to irrigation), but the growth is faster than linear, possibly due to population growth being closer to exponential. Kyrgyzstan and Romania both display a stabilisation or a decrease at the end of the series, clearly associated with the collapse of their economies and the associated lack of inputs. Finally, Saudi Arabia is a clear example of very capital intensive innovation from the eighties onward.

[11] Another difficulty stems from the tradition of most national statistical services to report harvested areas instead of planted areas. This results in artificially reducing the effect of weather.

Table 2: coefficients of variation of linearly detrended yield series of total cereals, maize and root crops in selected areas and countries of the world (reference period: 1961-94; data from FAO, 1994)

	Cereals	Maize	Roots		Cereals	Maize	Roots
World	3	6	4	**Bangladesh**	7	21	9
Europe	6	10	7	**Saudi Arabia**	43	48	30
Africa	6	12	3	**Tajikistan**	23	36	20
Least dev.	3	6	3	**Thailand**	5	12	8
Egypt	7	10	6	**Australia**	16	16	4
Mauritius	55	55	24	**France**	6	12	10
Niger	15	24	12	**Romania**	15	19	26
Rwanda	12	22	16	**Spain**	14	8	5
Tanzania	16	17	18	**Mexico**	6	10	6
Kazakhstan	28	24	15	**USA**	9	11	3

Table 2 provides a sample of detrended coefficients of variation[12] in selected countries and areas. Although the aggregated values are meaningful only where the trend is reasonably linear, it may come as a surprise that the CV of the USA and France, two of the main grain producers, are still close to 10 %. It is also typical that small countries such as Mauritius display high values, as the spatial averaging effect is less marked.

Figure 4 shows how yield variability in Africa depends on water supply. Two factors are actually at work: relatively better soil storage in humid climates, long seasons in humid areas and, of course, the fact that, almost by definition, rainfall variability is higher in low rainfall area.

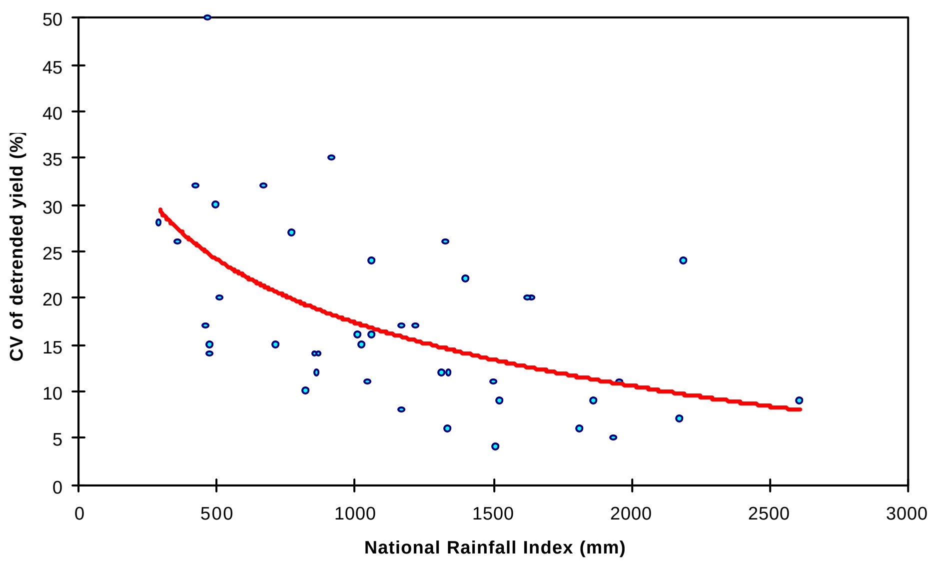

Figure 4 : coefficient of variation of detrended yields in Africa (1961-94) as a function of National Rainfall Index.

[12] The "detrended coefficients of variation" were obtained as follows: take the 1961-94 yield time, compute linear trend (regress yield series against time), subtract regression line to obtain residues (departures from trend), compute Standard Deviation of Residues (SDR), express SDR in percent of the average of the original time series.

Due to the skewed distribution of rainfall, expected amounts are less than the average. According to a global study by Oldeman (1987), dependable rainfall (defined as the amount falling during at least 3 years out of 4) is usually of the order of 80% of the average. For areas where annual rainfall exceeds 100 mm, Le Houérou et al. (1993) found that the coefficients of variation of annual rainfall increases from 10% (rain forest climate) to more than 50 % under arid conditions.

Altogether, due to soil storage and management, agriculture does thus somewhat compensate the natural variability of climate. It remains that, on average, variability is one the main factors why actual yields remain well below the local agro-pedoclimatic potential.

3.5 Climate change

3.5.1 Some facts

One of the main conclusions of the latest IPCC assessment is that the *atmospheric concentrations of greenhouse gases, inter alia carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have grown significantly*[13]*: by about 30%, 145%, and 15%, respectively. These trends can be attributed largely to human activities, mostly fossil-fuel use, land-use change and agriculture* (IPCC, 1996a, summary for policymakers)

The overview in

Table **3** shows the striking difference between the relative importance of CO_2, now the main greenhouse gas (GHG), and water vapour.

It is also relevant, in this context, to stress that agricultural sources of several GHG are very significant:

- CO_2, an estimated 25% stems from agricultural sources (deforestation: 20%, biomass burning: 5%). The agricultural sources appear to be declining relative to fossil fuel use;
- CH_4: there is a lot of uncertainty about the figures. About 70% could be derived from anthropogenic sources, of which 20% each each domestic ruminants, biomass burning and rice production. The remaining 10% is usually assigned to "other waste products". Natural wetland could be responsible for about the same emissions as rice fields;
- N_2O, tillage 44%, fertiliser 22% and biomass burning 9%. Agricultural sources seem to be stabilising, while the relative importance of energy is on the increase.

Table 3 : summary of green-house gas emissions and characteristics. (1) ppmv and emission in Gt; (2) ppbv and emission in Mt; (3) ppbv and emission in Kt; (4) pptv; (5) weighted average of the CFCs, excluding the ones that have been phased out; (6) Global warming potential, i.e. the warming potential relative to CO_2 over a 100 year period. Based on IPCC 1996a, Schönwiese 1995 in Zwick 1997a and Zwick 1997b.

	Concentration	Emission		Greenhouse

[13] The growth rates refer to 1992 in comparison to pre-industrial levels.

	Pre-industria	1994	volume	change % year^{-1}	Lifetime years	GWP (6)	radiative forcing %	
							Pre-	1990
CO_2 (1)	280	358	7.4	0.4	50-200	1	22	64
CH_4 (2)	700	1720	506	0.6	12	11	3	19
N_2O (3)	275	312	12.9	0.25	120	270	4	4
CFCs (4)	0	450	>970	3 (5)	12-50000	>3400		>2.5
Water							62	9

The scenarios developed by IPCC present the following data for 2100: + 1°C with 500 ppmv CO_2 (lowest), + 2.0 to 2.5 °C with 725 ppmv CO_2 (most likely) and + 3.5 to 5 °C with CO_2 above 1000 ppmv (worst case). According to Ehsan Masood (1997), if all developed countries kept to their Kyoto target, world temperature would still rise by 2.1°C by 2100. This is only 0.27°C lower than the "Business as Usual scenario" (BAU) resulting from no intervention at all to reduce emissions. This is to say that about 2°C increase by 2100 can be taken for granted.

Under the "virtually certain 'facts' to very probable 'projections'", Mahlman (1997) lists the following:

- climate has considerable inertia, and cannot be reverted over a short period of time;
- cooling effect of sulphate particles is insufficiently quantified;
- significant reduction of the uncertainties will require a decade or more;
- water vapour concentrations will increase in the lower atmosphere[14], and global mean precipitation could increase by 1.5 to 2.5 % per 1 °C of global warming;
- sea level rise may reach about 50 cm by 2100.

There is no scientific evidence that the frequency of tropical cyclones, storms or hurricanes would increase, nor should winds in mid latitudes (as opposed to tropical areas).

3.5.2 A discussion of potential impacts

Potential impacts on agricultural production have received a lot of attention (Kaiser and Drennen, 1993; Bazzaz and Sombroek 1996a; Helms et al., 1996; IPCC, 1996b and 1996c; Smit et al., 1996; EC 1997). Their extent will largely depend on the future concentrations of CO_2, as well as on temperatures, on the internal dynamics of agricultural systems, including their ability to adapt to the changes. Both are unknown, as indicated, because they will eventually depend on the interference of other substances (notably aerosol), on policy measures taken in the ambit of Framework Convention on Climate Change, and on the compliance of countries with the agreed protocols.

Note that the scenarios insist on temperature and CO_2, mostly ignoring or mentioning cautious hypotheses for other parameters. This refers, in particular, to the components of potential evapotranspiration (radiation and cloudiness, moisture, wind, extreme temperatures) and the water balance (rainfall, in addition to the previously listed variables) as well as, most importantly, the variability of future climate (Katz et al., 1992). In the

[14] ... in absolute terms. Relative humidity may not change significantly.

words of Reilly (1996), *the most "robust conclusion" that does emerge from the studies is that climate change has the potential to change the productivity significantly...*

It is also stressed that many changed-climate scenarios are derived from equilibrium models, i.e. they assume that climate has reached an equilibrium under, say, doubled CO_2, when it is obvious that climate will change gradually, and that agriculture will adapt and develop response mechanisms gradually as well. Changed-climate impacts assessments on current agriculture are, therefore, not very useful. Transient model outputs, i.e. model outputs which change gradually over time from the current to some future situation are being developed. In theory, they should be able to forecast weather years ahead, thus actually providing tools for seasonal forecasting. Of course, they still suffer from the difficulty to properly define boundary conditions, including CO_2 concentrations.

There is little doubt that the approach adopted by the IMAGE team (Alcamo, 1994; Alcamo et al., 1994) lends a lot of credibility to their projections: they "train" some components of the global models on past data (1970-90, sometimes longer) and verify that the current situation can be realistically simulated.

In comparison with global impacts on food production and food security (refer to Parry and Carter, 1998, for an overview and the relevant literature), impacts at plant level are **relatively** easy to assess, although still very uncertain (see Bazzaz and Sombroek, 1996a, for direct and indirect effects on plant physiology). They include the following:

- a positive effect of higher temperatures on crops, including longer growing and grazing seasons in some areas, but largely dependent on the relative difference between night-time and daytime temperatures;
- shorter crop cycles;
- CO_2 fertilisation, with a more marked effect on C3 species than on C4 plants;
- improved water-use efficiency;
- modifications of coastal/deltaic agriculture;
- modified crop/animal and pest/disease relations, including new pests and diseases, and changes in economic return (including new opportunities);
- modified variability and risk patterns.

Major methodological difficulties are associated with up-scaling (extrapolating local models to the global scale: Körner, 1995; Fischer et al, 1996) and down-regulation (the fact that physiological effects measured under laboratory conditions may overestimate the impact in the field because the response fades away after long exposure times). This being well noted, the following could happen at the global/ecological scale, at least in a first step:

- new agricultural areas become available in currently cold climates, loss of land at high elevations[15] and high southern latitudes, modification of the current crop geopolitical balance;

[15] Particularly in tropical areas, the final impact will result from the balance between loss of area and gain of productivity. In Kenya, for instance, Fischer and van Velthuizen (1996) find a net increase of production.

- loss of carbon stored in peat and soil organic matter, modifying erosion patterns;
- human population movements, increased global insecurity;
- loss of existent biodiversity, and creation of "new" biodiversity;
- zonal migration of species, ecosystems, crops and animals. Complex modification of the interactions between species.

Very little is known about the spatial distribution of the more complex impacts. If expressed in terms of Gross Domestic Product from Agriculture (GDPA), and after making due provision for adaptation, impact could generally be positive in developed countries, and negative elsewhere (Fischer et al., 1994 and 1996). The authors also cautiously suggest that by 2060 there may be a relative decrease of hungry people, but an increase in Africa when expressed in absolute terms. In Asia, on the other hand, there would be both a relative and absolute decrease.

4. AGRONOMIC RESEARCH

4.1 Improving climate

Climates can be improved using a variety of traditional and modern methods and techniques, from microclimate manipulation (such as mulching), the orientation of the rows in row-crops and windbreaks through varying levels of water control[16] to artificial climates, for instance in greenhouses where temperature, light and CO_2 can be controlled.

While the techniques like those of frost protection using smoke (fires) and sprinkler, or hail protection and cloud seeding are very "hardware oriented", there is currently a tendency towards more sophisticated use of weather knowledge in models that assist farmers and herders in decision making. Strictly speaking, this is not (micro)climate manipulation, but a way to make optimal use of climate resources.

The dependence of many common pests and diseases on weather can be modelled and their probability of reaching critical levels can be forecasted with good accuracy. However, many farmers and livestock breeders carry out preventive control of pests and diseases, thereby avoiding almost all losses but also, and maybe more importantly, actually insulating their production from weather, and ensuring a better control over their time and capacity to plan. It remains that, at least statistically, agrometeorological pest and disease models have the potential to reduce protection costs while reducing pesticide release into the environment.

4.2 Taking advantage of climate knowledge to manage variability

The first step in all climate-agriculture work is to *know* the climate, i.e. to collect long-term data and assemble them into climatic databases. But very often there is a mis-match between biological observations and weather observations: efforts should be made to collect at least basic information from the location of all agronomic experiments, and to

[16] It would be useful to have a proper typology of water control in agriculture!

ensure that extreme conditions are adequately measured[17]. As indicated above, climate plays a part at the many different levels leading from production or the harvest of wild products (including fish) to consumption, and the effect of weather and climate on all those levels is worth investigating.

It should also be kept in mind that *the definition of extreme agrometeorological events is broader* (than just weather), *as they include as well weather conditions conducive to the development of agents (like pests and diseases) that negatively affect agriculture (*definition adopted by WMO*)*. Extreme agrometeorological events thus include, for instance, desert locust outbreaks: rainfall in semi-arid areas can create conditions favourable to locusts, eventually leading to gregarization and swarms spreading over large areas. Fire as well can be included, as risks are very dependent on rainfall, moisture and winds.

The two previous examples stress the need to carry out both a monitoring of conditions favourable to pest, disease, fire, etc. development and, subsequently, to monitor the conditions which control the spread of the extreme agrometeorological event from its source to larger and sometimes distant areas.

Schematically, the use of climate knowledge is relevant for the following "categories":

- types of "organisms" : crops, pollen and seeds; livestock, poultry and freshwater fish; pests, diseases and parasites; national parks and wildlife;

- monitoring growing and post harvest conditions. This can be done by using models, identifying critical thresholds, forecasting the impact of drought, fires, hail, frost, vernalization, extreme agrometeorological factors;

- advice, as basis for decision making: meteorological forecasts, trafficability, farm operations, dissemination of pathogens and pollutants, response farming and precision farming, advice to farmers and herders, irrigation and drainage;

- technology (climate as resource): water conservation and harvesting, occult precipitation, artificial climates (greenhouses, stables, tractors and farmhouses), agroclimatic zoning, agroclimatic risk (insurance), microclimate modification, windbreaks;

- forecasting: yield forecasting, forecasting quality of production, forecasting phenology (harvest time and labour requirements), rangeland production, international markets as a result of production and resulting prices;

- methodologies: data technology in the broadest sense (collection, standardisation, software, estimation of missing data, random weather generators, gridding), modelling production, development, impacts...

[17] Typical examples include rainfall in semi-arid areas, for which a reliable automatic measuring system has yet to be developed, or reasonably wind-proof anemometers in cyclone areas. Impact assessments and forecasting continue to be hampered by the absence of reliable weather and crop damage data.

Forecasting in general deserves a special mention in the light of the interest triggered by the latest 1997/98 El Niño/Southern Oscillation (ENSO), in particular because of the lessons than can be learned..

To start with, El Niño provides a good example of a relatively reliable seasonal forecast, which can be taken advantage of by governments and the agricultural community alike. Unfortunately, like all forecasts, the actual magnitude, location and other features are affected by error. The methodology of whether to take management decisions, taking into account ENSO information, must be based as much on economic data as on simulated potential agronomic impact scenarios.

Such impact scenarios are not ENSO specific but constitute only a special application of a weather or climate forecast. Current discussions about how to react to El Niño are useful only if they lead to long-term solutions, in particular if efforts are made to improve all seasonal forecasts, if decision/simulation tools to be used by governments and farmers and ranchers are available, and if climate/weather impact on agriculture is seen as much in terms of opportunities (taking advantage of unusually "good conditions", commodity market opportunities and planning, etc.) and more efficient use of climate resources by farmers rather than only in terms of loss mitigation.

The above mentioned decision tools must be developed in collaboration by national climatological services, research and agricultural and livestock extension and tested locally, including a critical evaluation of the impact of the advice on agricultural output in terms of quantities and regularity.

In practice, the decision tools are tables/flow-charts or software that assist farm-level management decision-making based on three types of inputs:

- the knowledge of local environmental/agricultural conditions (reference data[18]);
- the measurement of local "decision parameters" by local extension officers, farmers and cattle breeders;
- economic considerations, e.g. cost of inputs vs expected output.

4.3 Adapt species and production systems

There are many examples of adaptation of agriculture to extremely difficult climates, for instance, flood recession crops on river banks and irrigation in semi-arid areas and outright deserts (Nile, Niger, Senegal rivers). Another technique uses low mud dams (usually not exceeding a height of 1.5 meters) in terrain depressions to collect run-on water during the very short seasons of the desert margins. As water infiltrates and evaporates, crops are planted at the receding edge of the water and grow on soil moisture during the dry season, thereby enjoying low pest incidence due to low atmospheric moisture and a high production

[18] A simple example of this could be, for instance, a threshold of air moisture or sunshine duration to decide on pest risk, or a threshold of salt content of water to decide on irrigation-salinity risk. More complex applications require the use of models, which can usually not be run at the village level but require regular communications with a central office.

potential due to the virtual absence of clouds. In addition, the harvest is spread over several months, and is predictable.

Livestock is another convenient mechanism to collect the sparse biomass spread over large areas. In semi-arid areas it constitutes virtually the only mechanism for people to make a living in spite of very limited water resources.

More modern techniques are those of precision farming, though still beyond the reach of most developing countries, which adapt management to the micro-variations of the environment, in particular soil features.

The potential of biotechnology is huge; it includes:

- the breeding of plants and animals better suited to resist abiotic stresses (like high temperatures) through inter-specific crosses
- the development of morphological adaptations - such as stronger root development and more favourable Leaf Area Index - and physiological improvements to photosynthetic efficiency - like possibly CAM features in C3 and C4 plants
- more specific pest and disease resistance.

4.4 Mitigating climate change and no-regrets

Conjectured effects of climate change on agriculture are large, but uncertainties are such that specific protection measures (e.g. location- or species-specific) are unlikely to achieve their goal. It is rather through emission reductions, gradual adaptation (including evasion) and preparedness that agriculture will be able to cope with the new environmental setting. Protection is likely to involve structural measures with a sizeable cost.

The uncertainty associated with projections of climate change and assessments of impacts on agricultural potential calls for attentive preparedness, to readily take advantage of beneficial impacts of climate change and increased atmospheric CO2, to mitigate negative impacts of climate change where they cause loss of productivity, and to cope with the technological and social challenges of changing patterns of land productivity. In essence, this will require addressing many problems which concern farmers, foresters and livestock breeders and decision makers already today.

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

Such measures include:

- improved fertiliser use, as N_2O released into the atmosphere is a loss and constitutes a symptom of inefficient farming. Needless to say, the same applies to nitrates lost to the water table and surface waters;

- improved ruminant digestion through more efficient feeds or, when feasible, a shift to enzymic digesters;
- development of water harvesting and conservation techniques, as well as other improvements to crop-water management as an adaptation to rainfall variability;
- improved rice farming, as higher yields are accompanied by a **relatively** smaller loss of methane;
- improved soil carbon storage (carbon sink) while at the same time improving soil structure increasing water holding capacity;
- improved low-impact harvesting in forests, reduction of slash-and-burn agriculture, better soil protection;
- a growing of alternative energy crops.

The example of rice provides an interesting illustration of the fact that agricultural emissions of greenhouse gases should be linked to production rather than expressed in absolute amounts, in order to favour the most efficient production systems. Obviously, this criteria should also be kept in mind by plant breeders!

Finally, we mention energy crops as a way to close the carbon cycle, as well as carbon sequestration in soils and biomass. While modern fuels from biomass seem to have real potential in reducing fossil fuel consumption while generating income in rural areas, carbon storage in biomass often needs justifications which are not all relevant for agriculture, such as recreation and tourism, watershed protection, improvement of urban climates.

4.5 Some gaps

Several areas have received insufficient attention in the general field of climate-agriculture research, including both climate variability and change. They include the following:

- the collection of combined data-sets of climate and agronomic information needed for the development of realistic impact assessment tools for current and future climate. The agronomic information should include at least information on varieties, phenology, pests and diseases, management and yields. This is also a point noted by Fischer et al. (1996) when they suggest that *agricultural research would benefit from greater attention to macro- and micro-climate in all trials*;
- efforts should be made to improve climate (i.e. seasonal) forecasts. While this is a task for climatological research, there are already some cases (El Niño) where the forecasts have achieved a reasonable degree of reliability (Cane et al., 1994). It is up to agronomic research to determine the conditions under which the use of the forecast will improve sustainability of all types of agriculture (from crop agriculture to inland fisheries) in terms of economic return and food security;
- many global impact assessments are based on models designed for the level of the individual field. They are appropriate for farm and forest management, but inadequate for regional studies, if only because most of the required inputs are meaningless or impossible to obtain at regional scales (Fresco and Kroonenberg, 1992). Methods are needed that will allow to bridge the gap between the field and regional scales, as well as between "sectors" (e.g. combined rangeland species composition and livestock models). This

point is highlighted by Leemans and van den Born (1994) who stress that detailed process-oriented models are unsuitable for input data on a coarse spatial grids;

- the potential interactions between changed climate and other plant responses, for instance to mineral nutrition (Rastetter et al., 1997) need to be further investigated;
- equilibrium global circulation models provide little insight into the dynamics that will lead from the current situation to future situations 30 or even 100 years from now. Transient models should be used instead and tested against recent historical data. A model that cannot represent the current situation is unlikely to be useful in forecasting future situations;
- the question of rates of change: a thorough discussion of impacts on natural vegetation and landscape processes as function of rates of changes is still missing (Walker and Steffen, 1997), as well the links between ecological complexity and resilience.

5. PARTNERSHIPS

5.1 Overview of climate-driven activities in the CGIAR System

Much research work carried out in the CGIAR system bears a direct relation to climate and climate change:

- Breeding for yield stability in stressful (drought, cold, heat) and variable environments: maize and wheat (CIMMYT), barley and durum wheat (ICARDA), legumes (ICARDA: adaptation to high altitude), maize (IITA); breeding for earliness: spring wheat (ICARDA), maize (IITA); breeding for increased productivity in flood-prone lowlands (IRRI). WARDA has a holistic approach to “drought resistance”, a mix of *physiological, phenological and morphological mechanisms for escape, avoidance, resistance and recovery*. Breeding should, therefore, be environment specific;
- Models to simulate management: improvement of water use efficiency (ICARDA), model research efficiency and outcomes in desert margins systems (ICRISAT);
- Improved decision making in several areas: (1) use of water resources: water conservation and management (ICARDA), comparison of agroforestry and crop agriculture in respect to sustainable water use (ICRAF), practices and breeds which improve water-use efficiency of rice (IRRI); (2) coastal zone management, fisheries and aquaculture (ICLARM)
- Climatic and land-resources databases, and conservation of resources: agroecological characterisation (ICARDA); aquatic biodiversity and coral reef conservation (ICLARM); baseline data on above-ground biodiversity (CIFOR)
- Climate and seasonal forecast: IFPRIs medium-term plan proposes "exploratory research" on economic and agricultural implications from medium to long-term climate forecasts;
- Management techniques to reduce CH_4 emissions from rice fields (IRRI), development of drought resistant upland rice;
- Management strategies: research into the effect of changing weather patterns on flood-prone riceland (IRRI); improved-impact harvesting of natural forests (CIFOR); alternative land-use strategies (CIFOR) and evaluation of international climate change mitigation policy options (CIFOR).

Furthermore, several centres have established scientific links with relevant organisations such as IGBP, in particular with the Global Change and Terrestrial Ecosystems (GCTE) project Focus 3 dealing with agriculture, forestry and soils (Tinker et al, 1996). The main items covered include the effect of global change on key agricultural systems, including food crops and pastures, changes in pests and diseases (with emphasis on weeds), effects on soils, on multi-species agro-ecosystems and on managed forests.

5.2 Links between UN and CGIAR on climate and climate change

There has been long-standing collaboration between FAO and WMO on climate and agriculture, often jointly with UNEP, UNESCO in the Interagency Secretariat of Agricultural Biometeorology, etc. (Gommes, 1995), directly or through the WMO Commission on Agricultural Meteorology.

Bilateral contacts of FAO with several CGIAR institutes have mostly centred on agroclimatic data (ICARDA, ICRISAT, CIAT) and the co-sponsorship of several meetings on the agrometeorology of specific crops, starting with rice (IRRI, 1980), sorghum and millet (1982; Virmani and Sivakumar, 1984), groundnut (1985; ICRISAT, 1986), or the characterisation of agricultural environments (Bunting, 1987)...

Several studies carried out under the auspices of the Interagency Secretariat of Agricultural Biometeorology have benefited from the logistic support, including data of the CGIAR centres, for instance the agroclimatology of the humid tropics of Southeast Asia (Oldeman and Frère, 1982).

In 1993, FAO and several CGIAR centres (ICRAF, ICARDA, ILRAD, ICRISAT) have collaborated in an effort to co-ordinate and harmonise databases and software for agroclimatic applications (FAO, 1995).

In an effort to ensure that proper consideration to impacts of climate and climate change will be given in the framework of the Interagency Committee on the Climate Agenda (IACCA), the FAO Council made the recommendation that the CGIAR system should be formally represented in the Committee.

5.3 Potential activities deriving from the Kyoto Conference

The recent Kyoto Conference (Dec. 1997) and the Kyoto Protocol explicitly recognised the links between climate change issues and sustainable development. In view of the new commitments and options, an increased role of the international agricultural community can be envisaged:

- participation in the development of improved assessment techniques for emissions and sinks of greenhouse gases in the agricultural sector, including terminology issues (e.g., managed and natural “forests”);
- participation in the discussion of details of trading emissions, its links with the clean development mechanism, and tools for developing countries to benefit from the trading with emissions ;

- assistance to countries in their compliance with new obligations deriving from the UNFCCC and the Kyoto protocol.

6. CONCLUSIONS AND RECOMMENDATIONS

This paper has stressed the close links that exist between climate resources and agricultural production potential, including biodiversity. A rapid evaluation of the chronic losses to agricultural production due to climate variability, and the potential losses brought about by climate change was also presented.

It is clear that we do not fully tap the potential of climate resources, and this can be improved with technological, management, institutional and legislative tools. But more than anything else, research has to provide better data, tools and methods to evaluate climate impact at scales ranging from the field to the region and the global scale (Fresco at al., 1997). A good illustration is provided by the IMAGE models which, as stressed by Alcamo (1994), was made possible only by the availability of improved data. At the farm level, crop, livestock, pest and disease models constitute essential management tools; at the regional level, they are indispensable for planning and for long-term impact assessments.

There is ample room for improved collaboration in the field of agronomic and climate research between governments, national and international research centres, as well as the UN system. This collaboration should focus first on the identification of the areas most vulnerable to climate impacts on agriculture, their typification and classification, and mapping. Fertile climates should also be assessed properly, both in terms of production potential and in terms of their resilience and preparedness to cope with increased demand, particularly in areas near to those where the largest impacts are foreseen. Bazzaz and Sombroek (1996b) insist as well on the need to identify large local differences.

Agronomic research must also improve the resilience of production systems and agricultural environments to variability and change, not only in a no-regrets perspective, but also with a view to building agronomically and economically more sustainable systems in the most vulnerable areas.

Reilly (1996) suggests that there is a need to map the robustness of current farming systems to variability. He also stresses the importance of genetic variability as a source for adaptation. Similarly, Bazzaz and Sombroek (1996b) stress that modelling has to be more comprehensive to include the feed-backs among biophysical, economic and technological mechanisms. This is also one of the main emerging questions listed by a recent synthesis of GCTE and related research. The authors (Walker and Steffen, 1997) go further as they include environmental, political and institutional feed-backs as well.

New constraints to agricultural productions will no doubt derive from the implementation of the international climate agreements, such as the Montreal protocol (phasing out methyl bromide) and the Kyoto protocol. Countries are committed to report accurately on their emissions from all sectors, and their plans to reduce them. This entails several difficulties, from methodological to institutional. Agronomic research has a role to play in most of them;

the CGIAR System and FAO should advocate the fact that, just like energy efficiency is a recognised target, the improved efficiency of agriculture derives directly from the international commitments.

Not only will absolute amounts of greenhouse gases be reduced, but the clean development mechanism should be used to ensure that emissions per unit of production should decrease, this is to say that efficient agriculture should be rewarded. For instance, the intensification of rice cultivation may produce large quantities of methane, but when expressed in terms of unit of methane per unit of rice, properly managed fields are more efficient than low yielding ones.

Next to constraints, there will also be new opportunities which agriculture has to prepare itself for in areas such as energy crops, carbon sinks in the form of standing biomass and soil organic matter. And, of course, biotechnological research will contribute to the development of more efficient plants. The CGIAR and international organisations must ensure that improved profit will not be the only criterion adopted by the developers: resilience to stressful environments (where the term is specifically meant to encompass not only the physical environment), more sustainable management techniques and the stability of yields are equally important.

Finally, international and, perhaps more so, national agronomic research have to ensure that national decision makers recognise that climate variability is a fundamental and more immediate concern than climate change, but that it constitutes the conceptual and methodological key to climate change preparedness.

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