Sustainability Natural Resource Management[1]

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1. Introduction

The title of this conference and the title of this particular workshop provide some guidance for papers to be presented in this workshop. The keywords are: (1) globalization, (2) science and technology, (3) education, and (4) sustainable development. Clearly, these are wide-ranging topics and, in addition, notions such as ‘globalization’ and ‘sustainable development’ are not very sharply defined and may mean different things to different people.

The UNU Institute for Natural Resources in Africa (UNU-INRA), Accra, Ghana, deals primarily with strengthening institutional capacities for research and education in sustainable management of natural resources in Africa. Hence, in order to make a somewhat focused and hopefully meaningful contribution to the discussion on the topic of this workshop, the emphasis in this paper will be on the notion of 'sustainability' in relation to management of natural resources (NRM).

Sustainable development has been defined by the World Commission on Environment and Development (WCED) as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. The report of the WCED, published in 1987, is also known as the “Brundtland Report”, in recognition of the chairperson of the WCED, Gro Harlem Brundtland. The definition emphasizes the inter-generational equity, but also a fair distribution of wealth among all nations in the world today, through “meeting the needs of the present”. The latter is obviously not the case in the world today and the recognition of this is reflected in the adoption of the Millennium Declaration by the UN General Assembly in September 2000. This declaration and its embedded Millennium Development Goals (MDGs) can be seen as a practical way of achieving a world where “the needs of the present are met” in an equitable and fair fashion.

Based on the Brundtland definition of sustainable development, the sustainable management of natural resources in the context of sustainable development would thus assume that natural resources are managed in such a way that (1) a livelihood is provided to the actors in the management process, (2) that future generations can make the same or similar use of these resources, and (3) that non-renewable resources are managed in a rational and conservative way, with an emphasis on recycling and exploring alternatives that make use of renewable resources. What this definition tries to capture is that there are two main aspects to sustainable NRM: a socio-economic aspect and an environmental aspect. In addition, there is an aspect of inter-generational equity: future generations should be able to make use of the bio-physical environment in much the same way as the present generation.

This paper will not deal with non-renewable resources such as fossil fuels and mineral resources, but is should be stated that even natural resources, such as soil, water, and biota (life forms), may include renewable as well as non-renewable components, depending on the nature of the resource, the geographic location and the time-scale considered. For example, some groundwater resources may be fossil and thus non-renewable, but when climate changes over a period of thousands of years, local climates in some areas may become wetter and thus recharge aquifers that were earlier considered to contain ‘fossil water’. As another example, soil is essentially a non-renewable resource on a time scale of, say, 50-100 years, except possibly in areas where active sedimentation (water, wind) takes place or can be induced. However, on a time scale of thousands of years, new soils may be formed under suitable climatic conditions. Similarly, biological resources (plants, animals) may disappear, but on the time scale of evolution new life forms may develop, containing genetic materials similar or equal to the materials that were lost in an earlier stage of development of life on earth.

This paper will further focus on the bio-physical rather than the socio-economic aspects of sustainable NRM in relation to sustainable development, but it is understood that the socio-economic aspects are as important, if not more important in many cases, as the bio-physical aspects in achieving sustainability. If a natural resource management system is not economically viable or does not provide a livelihood to a farmer and his family on a sustained basis, then such a management system is **not** sustainable.

Sustainable NRM will be discussed in the context of 'development', that is, the objective of natural resource management is to achieve, or contribute to, sustainable development. The most important economic activity related to NRM in rural (= non-urban and non-industrialized) areas is ‘agriculture’, encompassing cultivation of food and cash crops, pasture management, forestry, agro-forestry, livestock-based systems, fishing and fish-farming, etc. Other economic activities in rural areas include tourism and recreation, and extraction of minerals (mining), among others.

The focus of this paper is further on the science and technology basis of sustainable NRM or 'sustainable development'. In the discussion we will touch briefly on opportunities and challenges created by 'globalization' with regard to science and technology education for sustainable development.

2. The Emergence of the Concept of Sustainability

In order to better understand what is meant by sustainability it may be useful to consider the developments and events, in particular in Western countries, that have contributed to the emergence of the notion of sustainability. The following overview highlights a few developments and events that have contributed to the concept of sustainability, can be clustered under four headings:

(1) Environmental issues
(2) Limits to economic growth
(3) Biodiversity
(4) Social issues

2.1. Environmental issues

Concern about the environment is not a new phenomenon. For example, the famous speech by Chief Seattle in 1854 raised several important issues related to environment and nature and indicated clearly how perceptions differed between the indigenous Americans and the Western settlers. However, it appears that this speech did not reach the general public until the 1960's when concern about the environment developed into a major issue in the western world.

The discussion about the quality of the environment had clear international dimensions from the outset, and culminated in major international conferences such as the UNCED conference in Rio de Janeiro in 1992 and the WSSD in Johannesburg 10 years later.

Early on, cases of acute poisoning by cadmium and mercury in Japan (Itai-Itai disease and Minamata Bay) drew a lot of attention. After the heavy metals, the attention shifted to the organic micro-pollutants, which posed a threat to the quality of natural waters and drinking water. This was then followed by many other compounds, including nitrogen and phosphorus, as sources of pollution of natural waters.

In a number of cases the pollution of the environment was caused by intensive, high-input agriculture: Residues of pesticides, herbicides, nematicides, etc., in surface waters and groundwater, cadmium in soils where phosphate fertilizers had been applied, and copper in soils where pig manure had been applied. Nitrogen and phosphorus caused eutrophication of surface waters and later on were also found in groundwater. Ammonia volatilization from certain nitrogen fertilizers (e.g., urea) and animal manures was identified as one of the causes of the eutrophication of natural waters and acidification (acid deposition) of forests and natural habitats. Emission of nitrous oxides from temporally submerged soils was identified as one of the causes of the decomposition of the ozone layer, and so on. Parallel to concern about the chemical pollution of the environment, there was an increasing concern about the quality of food products: consumers wanted food that was grown without the use of biocides and chemical fertilizers. This trend resulted in the emergence of alternative forms of agriculture, such as "biological" or "organic" farming, or forms of agriculture based on anthroposophic theories (e.g., Rudolf Steiner).

Environmental concerns rank high on the sustainability-list, even though meeting certain (chemical or biological) environmental quality standards is not always a requirement for sustainability. For example, there is no reason why crops could not grow on soils that are polluted with heavy metals, such as lead or cadmium. What matters is the availability of these toxic metals to crops and this is often low or can be lowered through management practices, such as liming. All one would have to do is to make sure that heavy-metal contents of consumable parts of crops are below established food-quality standards. However, people generally feel that crops grown in a polluted environment should not be consumed and that, in turn, a sustainable agriculture should not pollute the environment. As a result, “sustainable agriculture” was often interpreted by the general public as a form of agriculture characterized by a reduced input of chemical fertilizers and biocides.

A lower input of chemical fertilizers could (to some extent) be compensated for by more biological nitrogen fixation (e.g., by legume crops), a more prolific incidence of VA mycorrhiza in order to increase P-uptake efficiency, more emphasis on the role of organic matter in soils, promoting the use of animal manures and organic residues, etc. The scientific expression of these trends was the research into "integrated nutrient management".

The trend to use less biocides resulted in an increased interest in alternative methods of weed control and in "integrated pest and disease management". The latter refers to a blend of methods of biological control, breeding for disease and pest resistance, and soil and crop management, such as the introduction of alternative cropping systems (intercropping, multiple cropping) and wider crop rotations, date of planting, etc.

As a scientific corollary of these trends there was an increased interest in the soil ecology or the functioning of the soil biosphere. Also there was an increased interest in interactions between nutrients and the incidence of weeds and diseases. For example, high N may increase the susceptibility to diseases, because the higher amount of biomass results in different microclimate under the crop canopy, which may be favorable to the development of diseases, etc.

2.2. Limits to economic growth

During the 70's and 80's there was a perception among many scientists that there were limits to economic growth, posed by the presumed exhaustion of non-renewable resources (fossil fuel, minerals) and the pollution and degradation of the bio-physical environment, in combination with the growing population and changing consumption patterns. This resulted among others in the reports of "The Club of Rome". The first report, The Limits to Growth, published in 1972, considered 5 major trends of global concern: accelerating industrialization, rapid population growth, widespread malnutrition, depletion of non-renewable resources and a deteriorating environment. Although the assumptions underlying the analysis and the method for understanding the dynamic behaviour of complex systems have been questioned, the report was very influential and contributed to the feeling among the general public that there were limits to economic growth.

Prominent in the discussion were the issues of renewable versus non-renewable resources and the development of new technologies. The general inclination was towards the use of renewable resources and recycling of non-renewable resources. Efforts to reduce the dependency on fossil fuel resulted in an increased interest in renewable sources of energy, such as sun, wind, tidal movement and the earth' warmth (geothermal energy). It may be noted that nuclear energy, although a clean source of energy from the point of view of emissions, was not generally considered an alternative to fossil fuels, because of finite resources of nuclear fuel and problems with the storage of nuclear waste products, as well as the risk involved in operating nuclear reactors. The latter was only strengthened after the Chernobyl accident.

With regard to agriculture, the discussion focused on substituting renewable for non-renewable resources, and in general to use less "external" inputs, as essentially all of these external inputs would require fossil fuels to be produced. This contributed to the emergence of "low external input sustainable agriculture" (LEISA). The move to use less fossil fuel resulted in a decreased use of heavy machinery and an increased interest in minimum tillage and zero-tillage techniques. This in turn resulted in an increased interest in the role played by the soil biosphere in producing a stable soil structure. Other external inputs that require fossil energy in their production include fertilizers, in particular nitrogen fertilizers. With regard to nitrogen fertilizers the trends were to decrease the overall use of nitrogen and to replace chemical fertilizers (substitution) by alternative sources, such as animal manures or other organic products, biological nitrogen fixation (symbiotic), crop residues, etc.

2.3. Biodiversity

Organizations that are involved in the conservation of nature have been around for a century or more. Until recently they never attracted much public interest. The conservation of nature is to some extent a separate issue from the environmental quality. The latter is largely defined in chemical (abiotic) terms and has to do with the contents of hazardous compounds (heavy metals, organic micro-pollutants, biocide residues) in the soil, in natural waters and in our drinking water, in the air, in our food, etc. In principle, in a world where there would not be a single bird left, the quality of the air, soil, water and food could be excellent. On the other hand, birds are part of many terrestrial and aquatic food chains and ecosystems, and their disappearance would have an effect on these ecosystems, whereas the disappearance of birds in itself would probably be caused by pollution of the environment, such as the accumulation of biocides (DDT) in certain food chains, which nearly lead to the extinction of certain birds of prey in Western Europe. The point is, though, that although bird populations may to some extent reflect the quality of the environment, their presence itself does not necessarily improve the environmental quality (other than the well-being of bird watchers).

Nevertheless, even though conservation of nature is not identical to environmental quality, nature conservation got a tremendous boost from the environmental movement. Many people did not distinguish between the two issues and started being concerned about the disappearance of species in our natural environment: birds, mushrooms, butterflies, lichens, whales, etc. The interest in organizations like Greenpeace and the World Wildlife Fund grew enormously. In the Netherlands, the membership of the Union for the Protection of Nature grew from less than 100,000 to more than a million.

To some extent the conservation of "biodiversity" is the rationalization of this movement. People started recognizing that the disappearance of many life forms resulted in the loss of genetic diversity and that this genetic diversity in turn could be of (economic) interest to us, now and in the future. The importance of plant genetic resources had long been recognized, but the issue was now broadened to include other life forms, including those making up the soil biosphere.

The consequences for agriculture were in the first place a move to decrease the use of biocides. Obviously, the objective of using biocides is to kill certain life forms. As biocides could not be entirely eliminated from agriculture, the interest shifted from broad-spectrum agents towards chemicals that are selective for specific life forms. Also, the rate of decomposition of biocides in the natural environment became important, as well as the chemical behavior and properties of the biocides and their decomposition products (residues).

The discussion concentrated on the trade-offs between effectiveness and environmental persistence of biocides: a biocide that breaks down quickly into non-hazardous compounds may be less effective against a specific life form, but attractive from the environmental point of view; a biocide that is highly persistent may be effective against specified life-forms, but poses a hazard to the environment. Also, this trend resulted in an increased interest in integrated pest and disease management and in the study of the ecology of agro-ecosystems.

Other consequences of the interest in biodiversity were an increasing interest in the collection and conservation of plant genetic resources (*in-situ* and *ex-situ*), more interest in the genetic characteristics of wild ancestors and land-races, and an increased interest in intercropping, multiple cropping, and alternative and wider crop rotations.

2.4. Social issues

The notion of sustainability also has a social dimension, as it assumes an equitable distribution of wealth in the present and intergenerational equity in the future. However, in many parts of the world, poverty, exploitation, and discrimination have persisted for ages and therefore it would be difficult to argue that systems based on, say, the exploitation of the rural poor could not be sustainable. Nevertheless, based on the Brundtland definition, issues such as poverty, discrimination, exploitation, or other forms of social injustice or deprivation, are contrary to the concept of sustainable development

The social dimension of sustainability may well be linked to a number of developments and events in Western countries during the post-World War-2 era: the democratization of the universities in the late 1960's, the emancipation of women, the decolonization process, the emancipation of all sorts of minorities claiming their rights, the end of the cold war, etc. Against this background there was a tremendous upsurge in extra-parliamentarian groups all over the world and in NGO's addressing a range of social issues.

“Globalization” became somewhat the rallying point of many of these social and emancipatory movements, as globalization was perceived by many as the dominance of the multinational companies, the globalization of poverty, the spread of 'western values', the consolidation of the economic and military supremacy of the industrialized countries, the monopoly of information gathering and dissemination through western news agencies, the dominance of the one remaining superpower, etc. Hence, it appears that at least one achievement of globalization was a degree of unification of a large number of environmental and social activists and movements on a common platform of “anti-globalization”. Although the concept of globalization may mean different things to different people, there is little doubt about some of the positive features of globalization, such as better access to information through the spread of ICT technologies, including the Internet. Nevertheless, in the perception of many, globalization per se has not made the world safer or more equitable, and disappointment about the lack of progress in realizing the substance of the Declaration of Human Rights in the post cold war era, has contributed significantly to the Millennium Declaration adopted by the General Assembly of the UN in September 2000.The Millennium Development Goals recognize that sustainable development is not possible without poverty alleviation and realizing a more equitable world, where the wealth is shared more equitably between nations.

One element in this context was that many people in western countries took an increasingly critical attitude with regard to the Green Revolution, which occurred in the developing world in the 1960's and 70's. The general idea was that during the Green Revolution the benefits went mainly to the richer farmers, with the result that the rich got richer and the poor got poorer. Whether right or wrong, this concept still influences many people's thinking about international agricultural research and development.

In the international development assistance programs of many Western countries, social issues are high on the agenda. Many programs aim at alleviating poverty, abolishing child labour, emancipation of women, protection of human rights, introduction of free-market economies, and establishment of Western-style democracies and civil society organizations. Not all of these topics gel well with local value systems, cultures and religious perceptions, and some forms of social injustice, such as discrimination of women, tribal minorities or lower castes, have been persistent for long times in some societies. Thus it cannot be stated that systems that contain elements of social injustice according to Western norms and values are necessarily unsustainable, but it seems that with better communication and sharing of values worldwide these traditional systems will come under increasing pressure. Hence, it seems that in the long run sustainability cannot be achieved without the full implementation of the Declaration of Human Rights.

3. Research and Education on Sustainable Natural Resource Management

In this section some elements of a "paradigm" or "conceptual or methodological framework" for research and education on sustainable natural resource management will be discussed.

3.1. The degree of sustainability

First it should be noted that we cannot measure sustainability directly. We should not expect to find universal laws that would pertain to sustainability. Sustainability is a quality (or qualification) that we attach to a system. Basically, we assess the degree of sustainability of an agricultural system by comparing a number of properties of that system ("metrics") with a set of specified criteria. The score on the sustainability scale is then a composite index made up of the individual, weighted scores. These "properties" could be the results of ecological or physico-chemical processes occurring in that system, but also the economic viability of that system or the degree to which it contributes to human welfare.

Sustainability is somewhat like the quality of food. We can determine the contents of hazardous compounds in the food and express the analytical results on a scale of zero to one, where one is the concentration above which the food is no longer acceptable for consumption. As long as the ratings do not exceed one, the food quality is acceptable, but the lower the contents of these compounds, the better the quality. Also, we have to assess the taste of the food, for example, with the use of a taste panel. In addition, the food should look nice, etcetera. This example does not suggest that sustainability is something like food quality, but it serves to illustrate that sustainability is a complex notion and that its assessment, on whatever scale, is to some extent based on arbitrary judgments.

The criteria that one uses to assess the degree of sustainability of a system should be reflected in the definition of sustainability. Obviously, the vaguer the definition, the more difficult it will be to quantify the degree of sustainability of a system and the more arbitrary our judgment will be. For example, if it is felt that "enhancing the quality of life" is an important criterion for measuring the degree of sustainability of a particular system, then our judgment will inevitably be somewhat arbitrary, as the "quality of life" is difficult to quantify.

For agro-ecosystems, economic viability and the effect of system dynamics on the environment and the resource base should be the major criteria.

3.2. The time scales

Although somewhat arbitrary, one could define time scales in relation to sustainability as follows:

Very short term:	1-5 years
Short term:	5-10 years
Medium term:	10-20 years
Long term:	20-50 years
Very long term:	50-100 years

where “time scale” is used in the sense of “time period considered”.

In principle, sustainability can be measured through quantifying the processes occurring in a particular agro-ecosystem, quantifying the interactions between these processes and system components, relating these processes and interactions to environmental and social conditions, and trying to predict the behavior of such a system over time, using comprehensive simulation models, at specified levels of input and based on certain assumptions with respect to social and environmental conditions, crop varieties, the incidence of pests and diseases, etc.

All of the processes in agro-ecosystems are functions of time and thus relate to certain time scales. One of the reasons why sustainability should be considered "over the long term" is to rule out short-term changes that do not affect the sustainability of an agro-ecosystem. For example, the application of nematicides will affect the soil mesofauna, in particular the nematodes. However, this effect is temporary, and normally after 1-6 months the effect on the soil-ecosystem will no longer be measurable (resilience of the system). Assuming that the nematicide is not preferentially adsorbed in the soil and that the original compound is all decomposed into non-hazardous products, the effect of the application of a nematicide on the agro-ecosystem is very limited or zero, even on the short to very-short term. The application of phosphorus or lime to agricultural soils usually raises the soil contents of P and Ca, respectively, over a period of 1-5 years. That is, there is an effect on the very short term, but not on the short to medium term.

Processes that have a limited effect on the short to medium term, but may have a pronounced effect on the long to very long term are, for example, loss of surface soil due to water or wind erosion, and the salinization of irrigated land. Erosion proceeds usually quite slowly and, depending on the depth of the soil and the nature of the top- and subsoil, it may take a long time before soil erosion results in measurable losses in productivity, not caused by losses of nutrients adhered to the soil particles. Similarly, salinization of irrigated soils may be a slow process, depending on such factors as the quantity and quality of the irrigation water, physico-chemical soil properties, the soil water balance (drainage!) and the cropping system.

Another aspect of the time scale is the farmer's perception of changes and measures to be taken. For example, "long term" means 20-50 years, or about a farmer's lifetime. It may thus not always be easy to convince a farmer to adopt practices that ensure sustainability on the long term, because in many cases a farmer will have to give priority the short and very-short term needs for food, fibre, firewood and feed. This points at the problem of adoption of strategies aimed at developing and implementing sustainable agricultural systems: if there are trade-offs between short- and long-term benefits, many (subsistence) farmers have no choice but to opt for the short term benefits.

In order to assess whether a particular agricultural system is sustainable or not, one would have to define that system in terms of time scale, space scale, factors and processes to be considered, etc. In addition, if one wants to assess the behavior of a system over time, one would have to specify the initial and boundary conditions.

It is clear that there is not one single time scale that is universally valid, or even one time scale that is more relevant than the other: a system that is not sustainable over a period of 5 years is unlikely to be sustainable over a period of 20 or 50 years, unless the direction of some processes changes drastically over time. In addition, the impact that time-dependent processes have on the productivity of a system also depends on the initial conditions. For example, if each year 1 millimeter of surface soil is lost due to erosion, and the soil is 20 cm deep (e.g., a Lithosol), then the impact of this process will be fairly dramatic over a period of 100 years and after 200 years the soil depth is down to zero. If under different circumstances the soil loss would be 5 millimeters per year, but the soil would be 5 meters deep (e.g., a deep loess soil), then after 100 years the effect of the much larger loss of soil (50 cm) on the productivity of the system could be rather limited, provided other properties (e.g., hydrology, soil nutrient status) would not be affected. Hence, the relevancy of time scales depends on the processes or properties studied, and time scales should be applied in a flexible fashion. The assessment of results of time-simulations against specified criteria depends on the initial conditions of the system: not 'all soil loss is equally bad', but 'soil loss from a shallow soil has a relatively larger impact on the resource base and the productivity of the system than soil loss from a deep soil', etc.

3.3. The space scales

Sustainable agriculture should also be considered on a certain spatial scale. Similar to what was said about a time scale, processes in soil also refer to space scales. For example, the study of micro-organisms refers to the micro-meter scale, whereas processes in the rhizosphere of a crop may be on the millimeter scale. Oxidation-reduction processes in periodically wet or submerged soils, or the diffusion of oxygen in soils, can be studied on the centimeter scale. The dynamics and distribution of nutrients in soil, following fertilizer application, can conveniently be studied on the scale of the soil profile (meter scale). Spatial variability of soil or crop properties can be studied on the field scale (square meter to hectare).

It is important to note that the way processes are described can be quite different for the different scales. For example, water transport on the micro-meter scale is described by the Stokes-Navier equations. Water movement on the meter-scale is described by Darcy's Law. Though this has been attempted many times, so far it has not been possible to derive Darcy's Law unequivocally from the Stokes-Navier equations, that is, there is no continuity between the 2 formalisms.

The study of the soil-crop water balance at the meter-scale is again quite different from the water balance in a watershed: in this case the theory may not be different but the scope and scale is completely different. The water balance on the scale of a watershed includes infiltration of rainwater, surface runoff, transport through gullies and watercourses, the effects of silt traps and bunds, the (3-D) movement of shallow and deeper groundwater through different aquifers, the effects of deep wells, the effects of vegetation (crops, trees, natural pasture), etc.

A completely different aspect of the space scale is the following: suppose one advocates the use of animal manures as a source of nutrients for agricultural land. On the scale of a hectare this may seem an attractive proposition: animal manure is an alternative (low-energy) source of nutrients and one can apply sufficient nutrients to compensate for crop removal and nutrient losses, provided animal manure is available in sufficient quantities. This would thus seem a nice sustainable practice. Now consider the scale of a watershed. Animals are likely to graze on marginal (common) lands on the hills surrounding the agricultural lands. These lands are not fertilized and the nutrients removed by the grazing animals are not replenished. Therefore, the fertility of these lands degrades, resulting in loss of vegetational cover and increased erosion of these soils. In addition, as far as nitrogen is concerned, animal grazing is a rather inefficient way of transferring nitrogen from the grazing lands to the agricultural lands, because of the high losses (leaching and ammonia volatilization). In short, on the scale of the watershed, animal grazing results in the rapid degradation of the grazing lands and thus is a highly unsustainable practice.

These examples illustrate that in discussing sustainable agriculture it is useful to define a space scale in addition to a time scale.

The definition of space scales is essential for the evaluation of agricultural systems. It is suggested that the performance of systems could be judged on the following scales (where applicable):

- the profile to field scale (1-100 meters)
- the watershed scale (1-10 kilometers)
- the scale of a suitably defined agro-ecological zone (of the order of 100 kilometers)

The proposed spatial scales would not allow for detailed studies on the functioning of micro-organisms in soils (micro-meter scale) or even mechanistic studies of processes in the rhizosphere (millimeter scale). The proposed scales do allow, however, for studying the following:

- The water balance, including the development and testing of technologies for water harvesting, water conservation, reducing surface runoff, increasing infiltration in soils, increasing crop water-use efficiency, etc.

- The dynamics of nutrients and organic matter, including the development and testing of integrated nutrient management systems, considering atmospheric deposition, making optimum use of fertilizers, animal manures and other organic products, recycling crop residues, optimizing biological nitrogen fixation and the incidence of VA-mycorrhiza, selecting crop varieties for optimum rooting properties and nutrient-uptake efficiency, developing cropping systems with shallow and deep rooting species, etc.

- The dynamics of soil and soil structure, as affected by soil tillage, mechanical impact of machinery, soil organisms, weather conditions, etc. The loss of surface soil due to water or wind erosion, and the testing of systems or management practices aimed at reducing soil erosion, such as vegetational covers, bunds, etc. Interactions between the water balance and the soil structure, e.g., surface sealing, water ponding on the soil surface.

- The study of the dynamics of pests and diseases in agro-ecosystems, as affected by soil and crop management, weather conditions and the use of biocides. The chemical and physico-chemical behavior of biocides in soil-crop systems and the environment. The decomposition rates of biocides in the environment. The study of host-pathogen interactions and the population dynamics of insects and mesofauna (e.g., nematodes), and the functioning of the soil ecosystem at the level of functional groups of organisms. The evaluation of disease- or pest-resistant crop varieties. The testing of integrated pest and disease management systems.

- The study and evaluation of traditional and alternative cropping systems, including the incidence of weeds and the evaluation of techniques for weed control (integrated weed control systems). The evaluation of plant genetic materials under conditions of farmers' fields and farmers' management. Agroforestry and social forestry. The interaction between crops and livestock. The *in-situ* conservation of plant genetic resources.

- The economic evaluation of farming systems. The assessment of human welfare. The evaluation of systems in terms of impact on women (gender), tribal minorities, etc. The use of (fossil) energy and human labor in farming systems. Short and long term productivity potential, yield and income stability, and equitability. Impact of policies on farmers' decision making. Trade-off values to forego a risky but highly productive system for a lower productive system which is less damaging to the environment.

Each of these processes, management packages or agricultural systems, would have to be studied at the proper space scale. Some of them, such as the water balance, would have to be studied at all three space scales.

3.4. The research focus

In addition to defining the time and space scales, one would have to further define the agricultural systems under consideration in terms of inputs, outputs, soil, crop, environmental and social conditions, in order to be able to investigate whether they are sustainable or not. Without going in detail, it will be clear that if the initial conditions of a system (or set of differential equations) are not clearly specified, the behavior of that system over time cannot be described. Similarly, if the boundary conditions are not specified, the behavior of a system cannot be described. One would have to indicate, for example, whether carbon dioxide contents, mean temperatures and crop genetic potentials can be taken as constant or that they change over time and, if so, how they change. Of course, predictions could be made for different scenarios, but these examples illustrate that long-term predictions on the behavior of agricultural systems require detailed information on environmental conditions and technological developments.

The development of improved crop varieties, and the collection and conservation of plant genetic resources remain important elements of the research program. The emphasis might shift more towards breeding for broad adaptability (tolerance to adverse abiotic conditions) and resistance to pests and diseases, rather than breeding for high yield potential per se. The improved plant genetic materials have to be tested at an early stage in marginal environments, in farmers' fields, under conditions of farmers' management.

Breeding for improved crop varieties depends upon assembling new useful combinations within the available genetic variability. However, in the recent past, breeding to ensure high and reproducible agronomic performance has led to increased genetic uniformity. Also most of the hybrids bred for high yield and/or resistance to pests and diseases have been developed from narrow genetic bases. Large scale adoption by farmers of such crops could lead to large-scale disasters when resistance is overcome by a known target pest or disease species. Alternatively, some non-target pests that break out sporadically may adapt to a widely grown cultivar. Hence resistant cultivars will cause the same selection pressure for pest adaptation whether the density of pests is high or low. While monogenic breeding has produced resistance to many pests and diseases, such as yellow rust in rice, Hessian fly in wheat, powdery mildew in barley, sterility mosaic in pigeonpea, fusarium wilt in chickpea and downy mildew in millet, resistance in released varieties may break down over relatively short periods, e.g., of the order of 5-10 years. For sustainable agriculture it might be desirable to breed for cultivars with increased genetic diversity through a wider use of polygenic traits.

Simultaneously, elements of sustainable resource management have to be developed and tested together with the improved crop varieties. These elements include techniques for soil and water conservation, integrated nutrient management, integrated pest and disease management, integrated weed control, cropping systems including a wide range of species to provide food (cereals, pulses, vegetables, fruits), fibre, firewood, construction materials (fences, houses), fodder/animal feed, etc.

The evaluation of the improved crop materials and technology packages should be done by multidsciplinary teams of scientists, consisting of breeders, agronomists, entomologists, pathologists, soil scientists, economists and social scientists. The latter are particularly important in multidisciplinary teams, as they ensure farmers' perceptions are reflected in the evaluation of technologies that are being tested and the design of research strategies.

Once a technology for sustainable resource management would be developed, there would be two directions of further development: one would be the upscaling of the technology for wider application, and the other would be the adaptation and adoption of the technology in a specific environment defined by socio-economic, policy, agro-ecological parameters. What is referred to here as a ‘technology’ would basically be a mix of elements of a technology package that would have to be adapted to the local conditions.

Simulation modeling linked to geographic information systems (GIS) would be required to extrapolate the results of resource management research from one agro-ecological environment to the other. The adaptation, and finally the adoption, of a flexible mix of sustainable resource management technologies at the farm level would require involvement of farmers. Without farmers' participation, no technology will be adopted, and systems that are not adopted by farmers cannot be sustainable. Hence, farmers' participation in the selection of elements and the design and implementation of technology packages is essential. Scientists in academic institutions can assist national programs in developing methodologies for on-farm research, rapid rural appraisals, participatory rural appraisals, reconnaissance surveys, etc.

3.5. Components versus systems approach

From the previous sections it follows implicitly that “systems” have to be studied through studying their “components” and then assembling “systems” through systems analysis, simulation models, or other integrative methodologies. This is because sustainability is a complex notion, or a composite index, that cannot be measured directly. Also, it would be difficult, if not impossible, to describe or model the time-dependent behavior of systems, comprising of soil, crop, livestock, climatic, socio-economic, cultural, religious and policy dimensions. Time-simulations of such systems would soon become meaningless, if only because of uncertainties in the initial and boundary conditions over time.

In order to study the sustainability of a system one has therefore to first disaggregate the system. Then one studies the relevant components or processes, such as the water balance of a soil or soil-crop system, the nutrient balances, the energy balance, the fate of biocides in soil-crop systems, etc. Then one compares the results of time- simulations with established criteria for the sustainability of each component. Following that, one determines the interactions between components. For example, the effect of nutrient availability on crop water-use efficiency, the effect of soil tillage on the functioning of the soil biosphere, etc. On the basis of an understanding of components and interactions, one could then assess the behavior and sustainability of a system.

In principle components *per se* cannot be "sustainable", because the notion of sustainability refers by definition to a system as a whole and not to individual components of that system. Components, however, can score high on their individual sustainability scale and thus contribute to the sustainability of the system.

Also, each agro-ecological system is site-specific. The extrapolation of results from one agro-ecological environment to the other could be based on simulation modeling and GIS. It may be noted that in simulation modeling too, it is the individual components that one can relate to soil and climatic conditions, rather than the entire system. However, the entire set of component-soil-climate relationships gives a fair indication of the behavior of the entire system as a function of soil and climatic variables, if properly calibrated and validated.

3.6. High- versus low-potential systems

The focus in research and education for sustainable natural resource management will be different for high- and low-potential systems. The benefit/cost ratios are likely to be higher in the high-potential systems, but more research may be needed in the low-potential systems, because they are more diverse in terms of soil, crop, climatic and socio-economic conditions and ecologically more fragile. Resource management packages for high-potential, high-input systems are closer to those practiced at experimental stations, and thus have largely been developed and tested. Low-potential, low-input systems cover a wide range of unfavorable soil and climatic conditions. Environmental concerns are also quite different for the two types of systems, and so are sustainability concerns.

Socially and economically the low-potential areas may also be more complex. There may be tribal minorities living in these areas, or generally more backward and traditional groups of people, which are less educated and have less been in contact with Western technologies than farmers in high-potential areas.

Low potential agricultural production systems may contribute little to the national economy, as measured by GDP are GNI growth. Many of these systems, at best, support a subsistence farmer and his family. In many cases, off-farm income would be needed to ensure a decent living for the farmer and his family, as his land may generate little surplus that can be sold in the market to generate some income. As the potential productivity of these agro-ecosystems is inherently low and as farming under such marginal conditions may lead to degradation of the environment, it would be tempting to recommend that the land be brought under forestry, agro-forestry or some form of pasture, rather than continuing the production of food crops. However, such a recommendation would only be realistic if there would be an alternative for the millions of poor and marginal farmers involved. Most countries in Sub-Sahara Africa and South Asia, where this problem is concentrated, could not offer alternative employment to these marginal farmers and thus for the time being attempts to develop sustainable farming systems for such marginal conditions remain relevant.

3.7. Enhancement of environmental quality and the resource base

The primary objective of agriculture is not to enhance the resource base on which agriculture depends, nor to enhance environmental quality. This does not imply, however, that among farmers in developing countries there would be no awareness of the need to enhance the resource base and the quality of the environment. In particular women farmers seem to be acutely aware of the state of the environment and the services provided by the environment. This is not surprising, knowing that in many developing countries women farmers are responsible for carrying water from the well to the house, for collecting firewood for cooking and heating, for collecting fodder for animals, and, above all, for feeding the children. When the groundwater levels drop and wells fall dry, women have to walk farther to find wells that still have water and have to lift up the water from greater depth. When the water quality deteriorates, women farmers are the first to find out, through the taste of water and food or diseases of their children. When trees are cut or die for other reasons, and no saplings are planted, women farmers have to walk farther to collect the ever scarcer firewood. Similarly, the availability of fodder is to some extent a reflection of the quality of the environment and the resource base, and again women farmers are the first to find out. Finally, because of the children and the animals, women farmers are more bound to the villages than the men, who go to the cities for work more easily than the women. These considerations may help to explain why in a number of cases women farmers seemed to be more susceptible to concepts of soil and water conservation, social forestry, etc. than men farmers in the same villages. However, the enhancement of the resource base requires investments in terms of organization, human labor, materials (e.g., saplings) and money (e.g., for chemical fertilizers, pumps, fuel). In many cases the farmers themselves will not be able to develop or sustain programs for the enhancement of the resource base, without outside assistance of government bodies or NGO's, for financial as well as organizational support.

3.8. Total factor productivity

It has been mentioned before that a system that is not economically viable cannot be sustainable. If a system does not sustain the people that form part of it, it cannot be sustainable. Of course, this is not specific for sustainable systems, it would apply to any kind of development model: systems that are not economically viable will ultimately disappear. The matter of subsidies is not considered here, but it should be noted that subsidized systems can be sustainable if (and as long as) the society is prepared to pay for them. For example, ecological (or: eco-friendly) agriculture in Switzerland is heavily subsidized, because the millions of tourists that visit Switzerland every year in the spring and summer, like to see cows in alpine meadows, haystacks, and whatever contributes to the beauty of the 'typical' Swiss landscape. Hence, even though this form of agriculture and the maintenance of the landscape is heavily subsidized by the Swiss government, this system would be sustainable as long as the tourism sector pays for this.

Total factor productivity (TFP) is a useful concept in measuring the productivity of agricultural systems. It is a necessary condition for economic viability, since it is measured in value terms, but it is not sufficient as a measure for sustainability. An example will illustrate. Suppose that at a constant level of inputs, the crop yields decline, that is, the productivity of the land decreases. Now assume that the prices of the crops increase in such a way that the income of the farmer remains the same in real terms (TFP=constant). Then the system would seem sustainable, but only from the economic point of view. From the physical/biological point of view, the system is unsustainable, because the productivity of the land decreases (possibly because of the build-up of diseases, micronutrient deficiencies, soil erosion or deterioration of the soil structure). The reverse situation is also conceivable. Yields may increase as a result of more efficient use of resources (energy, labour, nutrient use efficiencies). But if the prices go down, the income may remain constant. Thus, from an economic point of view, the system does not change over time. From a physical/biological point of view, the productivity of the land would increase, which means the system would do very well on the sustainability scale.

4. Conclusion

The concept of sustainability had strong international dimensions from the outset. The concept emerged first in the industrialized world and was then introduced in other parts of the world. Concern about the environment, the perception that there were limits to economic growth, the need to conserve biodiversity and a range of social and political issues, such as democratization of institutions and governance systems, emancipation of women and minority groups, as well as the decolonization process and the end of the cold war, all contributed to the complex notion of sustainability. Basically all of the above have strong international dimensions and are linked to globalization. Clearly, environmental problems such as pollution of the seas and oceans, the decomposition of the ozone layer and climate (linked to CO_2 emissions worldwide) are global problems. The global economy is probably the most globalized sector of all items considered. The globalization of the economy provides challenges and opportunities to many developing or transitional economies. Biodiversity conservation of plant species and especially of animals has global dimensions, for example, the conservation of whales and migratory birds. Finally, many (if not all) of the social and political issues that are considered relevant to the emergence of the concept of sustainability are global in nature: democratization, emancipation and, more recently, the 'anti-globalization' movement, as well as decolonization and the post war history (the cold war) are all global par excellence. Hence, it is no surprise that the United Nations took the lead in the discussion on sustainable development, first through the World Commission on Economy and Development, chaired by Gro Harlem Brundtland, who defined in its first report in 1987 sustainable development as a development "which meets the needs of the present without compromising the ability of future generations to meet their own needs". The publication of the WCED report in 1987 was followed by many other international events and culminated in the world conferences of Rio de Janeiro (1992) and Johannesburg (2002), and the adoption by the Millennium Declaration by the General Assembly of the UN in September 2000.

An important component of sustainable development is the sustainable management of natural resources (NRM) and the conservation of the bio-physical environment. Agriculture is the most important economic activity in the rural space and therefore any natural resource management system that is not economically viable, i.e., does not provide a livelihood to a farmer and his or her family is by definition unsustainable. Another observation is that sustainable NRM has social-economic as well as biophysical aspects and that in practice there may be a trade-off between these two sets of criteria. Sustainability as such cannot be measured, as it is a complex or composite index, which can be measured only by quantifying its component factors or processes, assessing their values or performances against a series of established standards, and then derive an estimate for the sustainability of the aggregated system. In addition, most if not all component processes of sustainability in relation to NRM are functions of time and space. It is therefore important to define the time and space scales when one studies sustainable NRM in relation to natural systems.

Research and education in sustainable NRM encompasses practically all scientific disciplines in the natural and socio-economic sciences, and thus have benefited from the unprecedented spread of ICT technologies in the past decades, most prominently the Internet, and the increased mobility of scientists worldwide. Although globalization has been questioned in relation to its social and economic aspects (cf. the anti-globalization movement), there is little doubt that its overall effect on science and technology related to sustainable management of natural resources has been positive, mainly through increased access to information, including satellite imagery at low cost or free of charge on the Internet, access to highly effective low-cost means of communication, the sharing of ideas and the exchange of academics, and the decreasing costs of gadgets such as cell phones and computers. Of course, in the low-income countries of South Asia and SubSahara Africa, a large segment of the society does not benefit from the opportunities provided by globalization, because of poverty and lack of access to basic amenities, such as electricity. Also, for the same reasons, technologies such as distance education have not made much headway in the poorer and more remote areas of the world. Hence, it is good to realize that technologies *per se* cannot solve socio-economic or governance problems, only people that make intelligent use of them can solve developmental problems.