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Time and spatial scales in ecological sustainability

Louise O. Fresco and Salomon B. Kroonenberg

It is argued in this article that ecological sustainability should be viewed with respect to distinct time and spatial scales, which are related to the hierarchical levels of land use, ranging from the individual farmer's field to the Earth as a whole. Production, efficiency and stability of agroecosystems are discussed, as well as resilience – the key dimension of sustainability which refers to the speed of restoration of output trend after a disturbance. Time and spatial scales of processes affecting sustainability are reviewed, in particular energy, air, water and nutrient flows, as well as climatic change and natural hazards. Natural resources with least resilience are soil nutrients, topsoil and biodiversity.

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Since the 1972 UN Stockholm Conference on the Human Environment, awareness of the inherent fragility of the world's ecosystems has grown, leading to vast numbers of reports reviewing the relationship between economic development and environment (a well-known example being *Our Common Future*).¹ The term 'sustainability' is generally used to indicate the limits placed on the use of ecosystems by humans, or more specifically to the way in which resources can be used to meet changing future needs without undermining the natural resource base.² Whatever the exact definition of sustainability, the term refers, nearly without exception, to a relatively limited time scale, eg decades or less. This approach implicitly assumes that all the factors influencing sustainability have similar time frames. Furthermore, the concept of sustainability is currently applied to land use systems of divergent geographical scales, from individual fields or farms to regions, countries or even the world as a whole. However, at each scale different processes operate, each at its own rate. In the same way, the distinction between renewable and non-renewable natural resources implies a specific time scale. Unconsciously we think of the rate of renewal of resources in terms of generations or decades, although renewal processes may be much quicker or slower.

In this article it is argued that ecological sustainability can be adequately defined only with reference to specific spatial and time scales. Some of the implications of different spatial and time scales in natural and agroecosystems are reviewed.

The nature of sustainability

The sustainability of natural ecosystems can be defined as the dynamic equilibrium between natural inputs and outputs, modified by external events such as climatic change and natural disasters. As soon as land is used by humans, the question arises as to what extent human extraction and disturbance interrupt the ecosystem's capacity to evolve. If sustainability is defined as a way of using land without disturbance of the ecosystem, no land use – and certainly no agricultural system – can be sustainable, with the exception of hunting and gathering at extremely low population densities. Sustainability in the sense of indefinite system

¹World Commission on Environment and Development, *Our Common Future*, Oxford University Press, Oxford, UK, 1987.

²TAC/CGIAR, *Sustainable Agricultural Production: Implications for International Agricultural Research*, FAO Research and Technology Paper No 4, FAO, Rome, 1989.

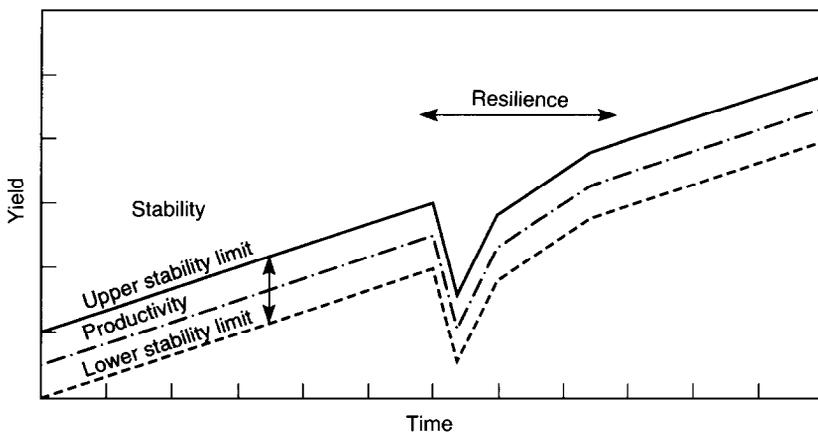


Figure 1. Production, stability, input/output and resilience.

Note: Positive trend of productivity curve refers to yield increase through technological improvements. Slope of productivity curve depends on input/output ratio.

maintenance is therefore a static concept that is inapplicable to agriculture and human land use. The primary driving force of increasing land use is human population growth. So in order to be sustainable, land use must display a dynamic response to changing ecological and socioeconomic conditions.

Sustainable agriculture refers to the use of agricultural land in such a way to ensure that over time no net quantitative or qualitative loss of natural resources occurs. However, no net quantitative loss must imply that we accept some inevitable changes, but exclude irreversible damage. In fact, we can distinguish three types of effect of land use on a natural resource base: disturbance of cycles (eg of the nutrient cycle), damage to system components (eg of the topsoil) and complete destruction of the system. This definition of sustainable agriculture is in effect a value judgement, defined under conditions described as disturbance, damage or loss. Exact values for each of these can only be defined in relation to the parameters and subsystems that make up the agroecosystem, eg to degrees of disturbance of soil microorganisms or of soil compaction. Acceptability of damage or disturbance depends on the time and spatial scales considered, for example deterioration of land qualities may be acceptable in small patches throughout the landscape or when they occur at a slow pace.

If it is accepted that sustainability means minimizing the disturbance and degradation of ecosystems and avoiding their destruction while keeping up their productivity, there are two opposed interpretations of sustainability: as an absolute value (a system is either sustainable or it is not), or as a relative value (a system is sustainable up to a certain degree over a certain time period). Sustainability as an absolute value is relevant in those cases where entire ecosystems are destroyed, and on long time scales. In the great majority of cases, however, absolute sustainability as a concept is meaningless because it is not related by the user to time and spatial scales. Four conceptual components of sustainability can be distinguished, which are visualized in Figure 1:³

- (1) production: total system outputs over time, ie total biomass;
- (2) efficiency: ratios of conversion of inputs into outputs from the ecosystem, including energy losses;
- (3) stability: degree of fluctuation around output (production) trend;
- (4) resilience: speed of restoration of output trend after major disturbance.

³C. Holling, 'Resilience and stability of ecological systems', *Annual Review of Ecology and Systems*, Vol 4, 1973, pp 1-24; H.T. Odum, *Systems Ecology*, John Wiley & Sons, New York, NY, 1983; G.R. Conway, 'Agricultural ecology and farming systems research', in J.V. Remenyi, ed, *Agricultural Systems Research for Developing Countries*, ACIAR, Canberra, Australia, 1985; and G.C. Marten, 'Productivity, stability, sustainability, equitability and autonomy as properties for agroecosystem assessment', *Agricultural Systems*, Vol 26, 1988, pp 291-316.

Each of these four components of sustainability is not only time-scale dependent, but must also relate to specific spatial scales.

Agriculture can be described as a hierarchy of nested (agro)ecosystems, that one may trace to greater complexity and longer time scales from the crop and animal community upwards through the farm system to the regional (and global) system levels.⁴ At each level, sustainability refers to other variables and boundary conditions and involves different temporal and spatial scales. What makes the concept of sustainability difficult to grasp is that system levels interact so that the characteristics of a given system are boundary conditions at the lower level (for example, national subsidies and prices influence farm management and resource allocation patterns that, in turn, influence the frequency of pesticide applications which may destroy natural soil fauna at the cropping systems level).

Production and efficiency

Production of an (agro)ecosystem is usually measured in terms of biomass (dry matter per unit area). Strictly speaking, production or output refer to total losses of matter and energy from the system, including losses through erosion, leaching, volatilization, etc. Outputs can also be expressed per time-area unit. Agricultural production figures cover only the harvestable or useful proportions of biomass production, and are nearly always expressed in relation to area, although output can also be related to units of scarce resource (nitrogen, labour) or seed.

Natural ecosystems such as tropical rainforests or savannas, once developed as a climax vegetation, have a more or less constant biomass production per time unit. By definition, crop and animal production implies seasonal and annual variation in land cover and outputs. The spatial aspects of production include variability in land area taken into production, ranging from extensive monoculture to mosaic patterns of fields and fallows.

Efficiency refers to the way production factors or inputs are combined to produce outputs, ie the conversion ratios of each input into output. In principle, efficiency can be measured per unit of scarce input factor, eg land, nutrients, energy or water. It has been demonstrated that, in contrast to the law of diminishing returns, input efficiency does not decrease at high production levels: no more than proportional increases in inputs are required if all inputs are increased simultaneously (the law of the optimum⁵). Efficiency, therefore, does not decrease, and often increases when optimal growing conditions are reached. In other words, relatively fewer losses occur at higher production levels.

Sustainability has become a public and scientific issue as a result of increased pressure on land, resulting partly from population growth, which since approximately the last two centuries has shown a steep exponential curve. Progress in agricultural science since the second world war has made possible a linear rate of cereal yield increase per unit area from a mere 2 kg/ha/year to over 50 kg/ha/year. It is unclear whether future rates of production growth can keep up with population increases. Global population is projected to grow at 1.6% annually between 1988 and 2000 (from 5.1 to 6.1 billion, with 4.8 billion of these in the developing countries), with a projected 3.1% increase in demand for agricultural products.⁶ Agroecosystems will have to continue to produce increasing outputs of biomass per average time unit to meet

⁴L.O. Fresco, H. Huizing, H. van Keulen, H. Luning and R.A Schipper, *Land Evaluation and Farming Systems Analysis for Land Use Planning*, FAO/ITC/WAU, Rome/Wageningen, 1989.

⁵C.T. de Wit, 'Understanding and managing changes in agriculture', in J. Jones and P. Street, eds, *Systems Theory Applied to Agriculture and the Food Chain*, Elsevier, London, UK, 1990.

⁶TAC/CGIAR, *op cit*, Ref 2.

likely global demands. To do so will require further control of the production environment.

Throughout most of human history, a decreasing human/land ratio has led to intensification of production, ie a higher frequency of land use in time and in space, coupled with increased inputs per unit land area. Today in the developing countries agricultural land to feed people is usually obtained at the expense of biodiversity, and possibly also water resources if we consider the climatological effect of cutting vegetation, especially rainforests. Population pressure has led to the breakdown of classical long-fallow shifting cultivation systems, thus undermining the natural processes restoring the ecosystem. Rising population densities may also mean that farmers put a premium on short-term production to the detriment of investments in the sustainability of the system. However, it has also been convincingly argued that population growth means more labour availability for land conservation and that land degradation can also occur in areas of low and medium population density.⁷ In some cases, especially in Africa and the former USSR, the road to land use intensification leads first through extensification where large areas are cleared for very low input production. These are often sites of lower resilience and higher sensitivity, for which known agricultural practices are inadequate. Low production levels often imply poor plant spacing and establishment, which increase the risks of soil degradation.

Altogether different problems occur in well-endowed agricultural regions, mainly in developed countries, where price relations have led to excessive use of external inputs and related pollution.

There is a growing consensus that a spatial concentration of agricultural production on high-potential land would be the most sustainable strategy, leading to the most efficient resource use and the least damage to ecosystems.⁸ However, this option is often socially unacceptable. An alternative pathway to production growth would be to shorten the cycling of resources in a closed system, ie shortening the mean residence time of nutrients. This is currently only possible in totally artificial hydroponic systems; it remains to be seen how accelerated recycling of natural resources can be achieved with annual cropping systems, or perennial cropping systems, in order to ensure sustainable growth. The lower limit of recycling of resources is determined by meteorological factors (day length, season length) and genetic characteristics of crops (growth rates). Moreover, the intensity of agricultural land use is commonly limited by the build-up of pathogens requiring rotations or the use of biocides.

Stability

Agricultural production varies in volume and composition each year as a result of external factors (especially weather conditions) and also as a result of farmers' adjustment strategies and risk assessment. Stability describes the normal amount of fluctuation around a general production trend or the ability of a system to return to an equilibrium state after a temporary disturbance.⁹ It defines the limits of how much (yearly) fluctuation is still tolerable without disrupting the system. The borderline between fluctuation and disturbance is difficult to assess, and depends on the (statistical) reliability of the trend curve. This requires observations of crop and vegetation growth and its comparison with a sufficiently long period of meteorological records. Stability is expressed

⁷P. Blaikie and H. Brookfield, *Land Degradation and Society*, Methuen, London, UK, 1987.

⁸De Wit, *op cit*, Ref 6.

⁹Holling, *op cit*, Ref 3.

in dimensionless units. There are clear differences between the degree of stability between agroecosystems in different geographical regions, usually as a result of climatic factors, but also because of other, high-impact factors.

Stability is a feature of sustainability for several reasons. First, a lower than average production implies poor ground coverage and the risk of soil degradation. Second, surplus production often leads to losses, because farmers (or regional bodies) are not equipped to store such harvests, while food shortages mean that the goal of meeting human needs is not realized. However, a limited degree of fluctuation may encourage farmers to take certain risks and induce agricultural innovations.

At the level of the farm and the community or nation, instability and risk in some commodities may be compensated for by others in order to maintain overall output stability. Because stability derives from productivity, it can be expressed in similar terms, ie in trends of dry matter or crop output or in monetary terms.¹⁰ Third, and most important, sustainability does not mean stability in the sense of a steady state or a lack of diversity. On the contrary, it has been argued that long-term stability results from near-random, disorderly changes in crop and pest populations.¹¹

Resilience

Resilience refers to speed of restoration of the output trend after disturbance, ie the persistence of relationships within a system, and its ability to absorb changes in state variables, driving variables and parameters.¹² Resilience is independent of the system's productive capacity (highly productive systems may be very vulnerable to small disturbances such as pest outbreaks and, conversely, low-productive systems such as shifting cultivation may be less prone to disturbances). Disturbances may be interruptions due to external processes of a magnitude greater than the limits of stability of sustainability (eg natural disasters), but may also include the cumulative negative effects of agriculture itself, such as salinization, nutrient depletion and pollution. Resilience is also independent of stability, as has been documented extensively for insect populations where population fluctuations in the face of extreme conditions are absorbed due to the system's high resilience. Holling suggests that resilience is an evolutionary adaptation in response to extreme variations in the environment, whereas stability seems to occur under less extreme conditions.¹³ In contrast to the other three components, resilience is related to sustainability in the absolute sense. Failure of a system's resilience leads to destruction and therefore to absolute unsustainability.

Resilience has to be expressed in time and space units. In the life cycle of a tropical rainforest, the clearance of a relatively small (1–2 ha) plot for shifting cultivation implies a minimal disturbance compared with the total area under forest, and requires approximately 25 years before the same amount of biomass is restored. The clearing of large areas of forest, however, may lead to irreversible damage to the forest ecosystem, or at least disruption for hundreds of years. Resilience is linked to the sensitivity of the agroecosystem, but high resilience does not always mean low sensitivity to disturbance. Resilience is also a function of the type of disturbance. In extreme cases, major impact factors such as massive landslides may destroy the system entirely.

¹⁰Marten, *op cit*, Ref 3.

¹¹M. Kellman, 'Some implications of biotic interactions for sustained tropical agriculture', *Proceedings of the Association of American Geographers*, Vol 6, 1974, pp 142–145.

¹²Holling, *op cit*, Ref 3.

¹³*Ibid*.

Spatial scales of sustainability

At one end of the spectrum we can consider sustainability on a global scale. There is no net loss of nutrients or water from the Earth as a whole, though that does not imply that sustainability is guaranteed. The hydrological cycle on Earth is essentially a closed system, in contrast to its energy flows. Export of nutrients such as cassava from developing countries and its import for fodder in large capital-intensive livestock farms in the Netherlands balance each other on a global scale. In Lovelock's Gaia hypothesis, life itself is responsible for the sustainability of the global ecosystem.¹⁴ But even here external forces operate: climatic changes are caused by variations in the absolute amount of solar energy received by the Earth.

The sustainable nature of many natural ecosystems such as tropical rainforests is largely based on closed-system recycling of nutrients, and possibly also of water. In this manner rainforests are to some extent responsible for their own survival. However, in reality they are not a closed system because they use solar energy and atmospheric CO₂ for photosynthesis. The importance of tropical rainforests for global climate therefore implies that we cannot simply assess their sustainable character without considering wider spatial scales as well.

Lower-level agroecosystems on the field or farm scale are not sustainable because they need inputs from outside in the form of fertilizers, pesticides, irrigation water, improved seeds, capital goods, etc. Moreover there is a net loss of nutrients, water or soil cover as a result of man-made or natural processes. In other words, sustainability at the level of the individual field or land unit must be considered with reference to processes at a higher hierarchical level than the system under consideration.

Time scales of sustainability

Time scales of processes acting on ecosystems can also be viewed in a hierarchical way. A rain shower is an incident on a day, but a regular component of weather in a year. A year of drought is an incident in the lifetime of a farmer, but a regular phenomenon in that particular climate. An ice age is an incident in human history, but a regular phenomenon in Earth history. Sustainability has a different meaning in each of these time scales.

For each individual agroecosystem, whatever its scale, we might define internal processes, acting within its spatial and temporal scale, and external processes acting from outside the system. Productivity, efficiency and stability of an agroecosystem are functions of its internal dynamics, but resilience is defined with reference to the external processes affecting the system. Therefore the sustainability of the agroecosystem cannot be determined without referring to processes that act at greater time scales than the internal processes. This can be demonstrated by discussing the time scales of both internal and external processes acting on agroecosystems, concentrating on agroecosystems at the local and regional level, because that is the scale at which most decisions by farmers, extensionists and politicians are taken.

Time and spatial scales of processes affecting sustainability

Energy, air and water flows in lower-level agroecosystems

Each agroecosystem can be characterized by a unique combination of

¹⁴J.E. Lovelock, *Gaia: a New Look at Life on Earth*, Oxford University Press, Oxford, UK, 1979.

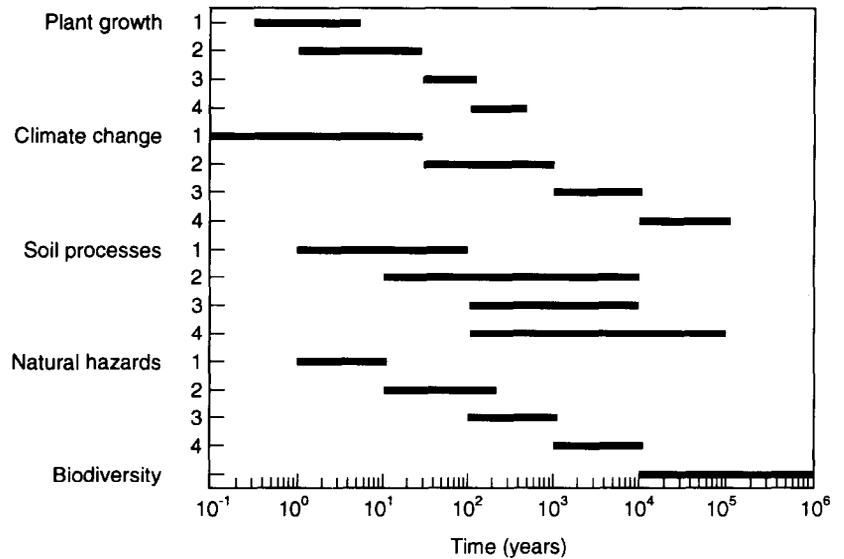


Figure 2. Time scales of processes affecting sustainability.

Notes: **Plant growth:** (1) length of one growth cycle of annual crops, including rotation up to 5 years; (2) length of one growth cycle of perennial crops; (3) length of growth cycle of production forest; (4) average biomass turnover rates of tropical rainforest. **Climate change:** (1) time scales of meteorological fluctuations: decades (smallest time unit used for simulation models of plant growth), seasonal and annual changes; variations up to 30 years, the minimal record length for reliable assessment of climatic parameters; (2) historic climate changes (cf Little Ice Age 1500–1850 AD); (3) Holocene (cf climatic optimum 6000 years BP); (4) Pleistocene, stadial/interstadial and glacial/interglacial oscillations. **Soil processes:** (1) time needed for complete erosion of topsoil; (2) time needed for severe nutrient depletion by leaching in humid tropics; (3) the same for the temperate zone; (4) time needed for formation of fully developed topsoil. **Natural hazards:** (1) frequency interval between gentle floods in alluvial areas; (2) the same for large disastrous floods; (3) frequency interval for andesitic volcanic ash falls; (4) the same for destructive volcanic eruptions. **Biodiversity:** time needed for restoration of macrofauna and macroflora biodiversity by evolution after major disturbance.

four resource flows, which differ in magnitude and in circulation time (see Figure 2): energy, atmospheric gases, water and nutrients. The first three are primarily supplied by external processes, which to a large extent determine the agroclimatological constraints. Except in totally artificial systems, farmers cannot do more than operate within these limits, although they may manipulate microclimate through mulching, shading or irrigation. The importance of these resource flows lies in their effects on production, efficiency, stability and resilience.

Energy is obtained from solar radiation, fossil sources and human or animal labour. Potential production is dependent on the annual amount of solar energy received (so reflects geographical latitude). Solar energy in itself is not limiting at the scale of local or regional agroecosystems. Changes in total intercepted solar energy occur as a result of global or extraterrestrial processes, but not as a result of agricultural activity itself, although management factors, shading, leaf area index, etc, affect intercepted radiation at the plant level. Neither are fossil energy resources limited, from an ecological point of view, although at each transition to a higher system level energy may be lost. A higher level implies also a higher energy content and throughput.¹⁵ Labour may be a limiting factor at regional and subregional scale, but not globally. In general, therefore, although energy losses may occur, they lead to inefficiencies, not to unsustainability.

¹⁵Odum, *op cit*, Ref 3.

Atmospheric gases are also supplied in unlimited quantities. Changes in their content due to human activity affect agricultural systems only via global processes, not directly, so they can be disregarded in assessing sustainability on infraglobal scales. Again, hydroponic and greenhouse horticulture can be the exceptions if extra CO₂ is externally supplied.

Water is required in all organic processes and water flows through the system allow nutrients to be transported. Water may be limited for various reasons, in particular climate. If land use is adapted to agroclimatic conditions, an improper use of limited water resources may adversely affect production, but leaks in the flow of water itself do not make an agroecosystem unsustainable. Moisture deficits, however, can pose severe threats to the stability (yield fluctuations) and even the resilience of agroecosystems through long-term effects on vegetation cover. Furthermore, the pollution of water sources with excess nutrients and/or biocides can affect sustainability in a dramatic way.

Energy, air and, to a lesser extent, water are therefore 'renewable' resources viewed at time and spatial scales of the local or regional agroecosystem itself. They are also replenished by global processes beyond the control of farmers, extensionists or politicians.

Climatic change

Agriculture began in a period of pronounced humidity (12 000–8000 years ago) with much higher precipitation than at present. Since then, rapid climatic changes have been experienced by our ancestors with both lower and higher precipitation and temperatures than now (Figure 2). These changes were also accompanied by concomitant changes in CO₂ content of the atmosphere. Climatic changes have caused considerable shifts in the global agroclimatic zones.

Climatic conditions have not remained constant for more than a few hundred years. Vita-Finzi found evidence of phases of deposition, channel erosion and river mouth aggregation alternated by tree cutting and management breakdown in most of the northern Mediterranean, resulting from fluctuations in climate.¹⁶ Whereas climate fluctuations on the scale of decades often cannot be resolved from large seasonal and annual fluctuations, historical records for the last five centuries clearly indicate worldwide synchronous glacier advances and retreats like the Little Ice age (c 1600–1850 AD). The present warming trend started before the extensive burning of fossil fuels. Models of future warming trends imply further latitudinal shifts of agroecological zones within a century.¹⁷

The amplitude of climate fluctuations increases when longer time scales are considered.¹⁸ Historic temperature changes are in the order of magnitude of 0.5–2°C around present average annual temperatures. Temperature change from the most severe glacial to the warmest interglacial periods in temperate zones may amount to 5–8°C in the temperate zone on the land and 2–3°C in the tropics. Likewise drastic changes in precipitation have occurred. These trends are depicted in Figure 3.

This implies that the agroclimatic zoning on which agricultural potential is judged is not stable but constantly changing. Sustainability of production systems is often assessed using models that simulate only a single cycle of crop growth under present climatic conditions. The predictive value of these models is therefore limited. Flows of energy, atmospheric gases and water at the global scale change quickly enough

¹⁶C. Vita-Finzi, *The Mediterranean Valleys*, Cambridge University Press, Cambridge, UK, 1969.

¹⁷M.L. Parry, T.R. Carter and N.T. Konijn, eds, *The Impact of Climatic Variations on Agriculture*, 2 vols, IIASA/UNEP, Kluwer Academic Publishers, Dordrecht, 1988; W.E. Riebsame, 'Climate hazard, climate change and development planning', *Land Use Policy*, Vol 8, No 4, 1991, pp 268–296.

¹⁸R.S. Bradley, *Quaternary Paleoclimatology*, Allen & Unwin, London, UK, 1985.

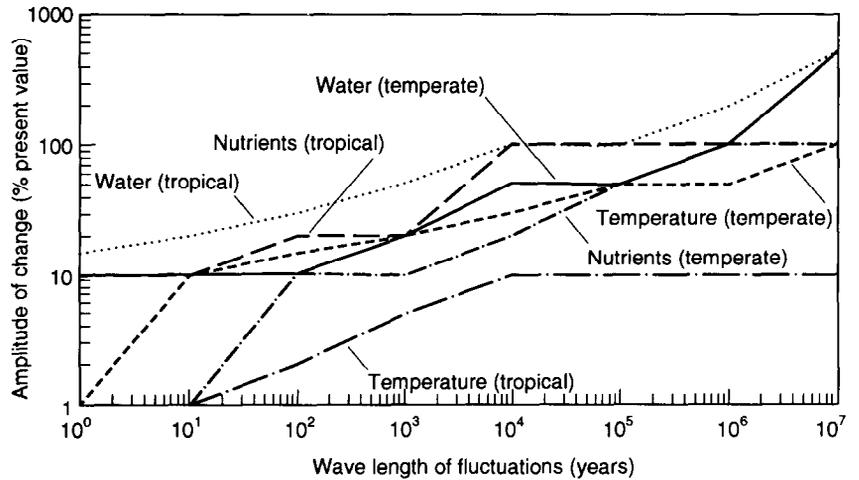


Figure 3. Amplitude and wave length of changes with time in the main biophysical parameters affecting production.

Notes: Average amplitudes are displayed as deviations in percentages from present average annual values. Numerical values are only rough approximations, and are strongly dependent upon geographical area. Separate curves are drawn for temperate regions and (humid equatorial) tropical regions. Water and temperature fluctuations on 1–10 year scale reflect weather variability, on 10^2 to 10^7 year climatic change as known from geological history. Tropical regions are shown with higher variability in water availability and less in temperature than temperate regions. Nutrient variability is based upon assumptions about rates of leaching in temperate and tropical climate on the one hand, and fresh supply by periodic volcanic eruptions, flooding and stripping of weathered bedrock on the other hand (see Figure 2). The general positive trends imply that the larger the time scales considered, the greater the magnitude of changes to be taken into account in assessing sustainability of land use systems.

to affect sustainability of agroecosystems at lower hierarchical levels of time and space (Figure 2). TAC/CGIAR state that climatic changes are likely to proceed at such a slow rate that the adaptation of agricultural practices, species and varieties is unlikely to pose special problems.¹⁹ However, climatic change in the recent past shows that it is pointless to extend scenarios for sustainable land use for more than 100–200 years if these changes in external conditions are not taken into account.

Soil nutrient flows

Soil nutrients have an entirely different time and spatial scale of cycling in agroecosystems. Natural ecosystems have a fairly closed system of nutrient recycling, generally requiring about 200 years to turn over (Figure 2), eg in tropical rainforest and old-growth evergreen forests in the southwestern USA. Some losses of soil nutrients by natural leaching always occur, and they are not easily replenished by natural processes, except perhaps for nitrogen which may come from the atmosphere. The source of all nutrients except N and C is rock and soil minerals. These nutrient pools can be restored from external sources through fresh volcanic ash additions; depositions of young fluvial or marine sediment on top of leached soils in alluvial areas; wet and dry deposition through rain and wind; or erosion during ice-age aridity leading to removal of leached topsoils and exposure of fresh bedrock in upland areas (next ice age in 23 000 years).

Over wide areas of non-volcanic non-alluvial character nutrient losses are irreversible on a human time scale, though not on a geological time scale (Figure 3). In agroecosystems, nutrient losses occur when the

¹⁹TAC/CGIAR, *op cit*, Ref 2.

original vegetation is cleared, by export of harvested crops and by increased leaching and soil erosion. Losses must be replaced (ie through fertilizers) and if replacement does not occur, agroecosystems degrade and are unsustainable. Sustainability-enhancing adaptive mechanisms developed by farmers (fallowing, manuring, crop rotation) and regional measures (erosion control and reforestation) are generally insufficient to balance losses occurring through land use in the long term. The sustainability of traditional agroecosystems is based on careful exploitation of microniches (such as terrace borders, ash and organic matter concentrations in the field), and detailed management of individual plants. These systems are rarely adequate to produce high outputs per unit labour and area, but may be very stable as long as population pressure does not increase.

It follows that soil-related flows are of paramount importance in the sustainability of agroecosystems of local and regional scale, since there are no global nutrient resources from which the soil can draw in the short run. Regeneration of nutrient losses is a direct responsibility of land users at local and regional system levels.

Soil degradation

The formation of organic matter in topsoil is a natural process, which in many cases had already started about 10 000 years ago or before. Current average annual per capita food consumption of 0.75 tonnes encompasses annual per capita soil erosion of 5 tonnes.²⁰ The impact of cumulative losses of topsoil on crop yields, while very variable, may be as high as 40% of yield reduction.²¹ A study forecasting production losses resulting from erosion in Botswana and Sierra Leone yielded very small losses over a short planning horizon of roughly 20 years, irrespective of whether improved or traditional management were adopted.²² Extension of these processes over longer time scales, however, always results in significant soil losses until indurated layers below the surface have been reached. Soil erosion is strongly dependent upon soil type. Farmers in the Andes and Southeast Asia may cultivate crops on andosols on steep slopes for hundreds or thousands of years without serious damage to the topsoil. On the other hand, soils in the Amazonian lowlands or the Himalayan mountains can be extremely vulnerable to soil erosion.

If, as is the case in many areas, the rate of soil erosion exceeds rates of soil formation (Figure 2), no sustainable land use is possible until the causes of erosion are removed (in large part this means restoration of vegetative cover). After complete removal of the topsoil it may take 100–1000 years before a new organic topsoil is formed.²³ Even under humid tropical conditions with easily weatherable unconsolidated material such as volcanic sands, soils of 20 years are too shallow for roots to develop freely. Decreasing nutrient supply can partly be compensated for by fertilization, but also other soil properties such as moisture availability and trafficability are adversely influenced by topsoil removal. There are currently no technologies available which can speed up processes of topsoil formation. Topsoil is therefore one of the most vulnerable resources to be protected.

Natural hazards

Agroecosystems in alluvial and volcanic areas are often only sustainable as a result of natural processes outside the control of the farmers. But

²⁰B.J. Skinner, 'Resources in the 21st century: can supplies meet needs?', *Episodes*, Vol 12, 1989, pp 267–272.

²¹M. Stocking and L. Peake, 'Erosion induced loss in soil productivity: trends in research and in international cooperation', paper presented to the IVth International Conference on Soil Conservation, Maracay, Venezuela, 3–9 November 1985.

²²Y. Biot, M. Sessay and M. Stocking, 'Assessing the sustainability of agricultural land in Botswana and Sierra Leone', *Land Degradation and Rehabilitation*, Vol 1, 1989, pp 263–278.

²³A.N. Gennadiev, *Pochvy i vremya* (Soils and time), Moscow State University Press, Moscow, 1990; H. Jenny, *Factors of Soil Formation*, McGraw Hill, New York, NY, USA, 1941.

natural processes affecting agroecosystems may have both positive and negative consequences. Cereals requires a dry period in order to ripen, but prolonged drought is harmful. Many temperate tree crops require close to zero temperatures to initiate flowering, but too severe frosts during flowering lead to damage. Volcanic ash falls give fertility to otherwise poor tropical soils, but volcanic eruptions destroy many of the same fertile lands. Gentle flooding brings fertile sediments, extensive flooding causes damage. A relationship exists between the magnitude of an event and its recurrence interval. This in turn influences the time an agricultural system needs to recover from the impact of a disturbance. Resilience with respect to natural hazards forms an important component of the long-term sustainability of agroecosystems.

Volcanism. Low-magnitude events in active basaltic volcanoes have small recurrence intervals (1–10 years) and though they may have positive effects on soil fertility, this is usually in limited areas. Higher-magnitude andesitic eruptions are more rare (with recurrence intervals of 100–1000 years) and spread ash over a much wider area, but the destructive power also increases.²⁴ The latter type of eruption is common in circumpacific tropical areas, and the volcanic ash falls are essential to soil fertility in parts of Central America, Indonesia and the Philippines. Weathering and leaching of nutrients from the ashes take thousands rather than hundreds of years, so active volcanic areas of this type receive more nutrients from ash falls than they lose by weathering.

The areal extent of loss of land and lives by volcanic disasters is very limited; most vulnerable are towns and lands within the course of volcanic mudflows and other pyroclastic flows. The high intensity of land use in active volcanic areas indicates that many people intuitively prefer to take the risk of volcanic hazards in order to take advantage of the fertility of the volcanic soils. Yet with increasing population density in these areas the impact of a destructive volcanic event is correspondingly greater.

Flooding. Gentle flooding brings fine calcareous alluvium to the farmers' plantain fields in the Sixaola Valley (Costa Rica) almost once a year (15 floods since 1970). Farmers whose fields did not receive flooding for several years complain about decreasing yields. But heavy floods, with a recurrence interval of about 30 years, often uproot plantain plantations and deposit up to a metre of coarse sand and boulders. Flooding in the Nile Valley (before the construction of the first dam in 1902) brought about 100 cm of silt per millennium, sufficient to replace nutrients without the risk of clogging the canals or raising the river bed. The historical record of the last 6000 years shows that, with the possible exception of the floodplains of the Nile, Indus and Mesopotamia, humans have never continued to maintain 'civilization' in one locality for more than 30–70 generations (800–2000 years).²⁵

Cultivation of wet rice requires yearly flooding; yet excessive flooding is the major hazard in its growing areas. More than half of the territory of Bangladesh is affected by severe flooding roughly once every three years. Riverbank erosion forces displacement of 1 million people per year.²⁶ Geological evidence points to floods of even larger magnitudes in the recent past – but with still larger recurrence intervals. Resilience with respect to flooding is high, as agriculture can be resumed within a few months or years after flooding, although losses of cattle or perennial tree species need more time to be overcome.

²⁴T. Simkin, L. Siebert, L. McClelland, D. Bridge, C. Newhall and J.H. Latter, *Volcanoes of the World*, Smithsonian Institution, Hutchinson Ross, Stroudsburg, PA, USA, 1981.

²⁵T. Dale and V. Carter, *Topsoil and Civilization*, University of Oklahoma Press, Norman, OK, USA, 1954.

²⁶P. Nutalaya, 'Flooding and land subsidence in Asia', *Episodes*, Vol 12, 1989, pp 239–248.

In all areas prone to natural hazards, sustainability is less likely to be achieved if longer time scales than 200 years are considered: the probability of disruption of the system by river floods, inundations by the sea and volcanic eruptions increases progressively.

Biodiversity

Biodiversity is the most vulnerable, least resilient natural resource. Lost genetic material can only be compensated for by evolution of new species. Geological history has shown that after a major global extinction event it takes several million years to restore species diversity (Figure 2). There are both temporal and spatial aspects to biodiversity.

Biodiversity under natural conditions is strongly dependent upon habitat. Through the Earth's history there has always been a gradient of biodiversity from the equator to the poles, with the highest numbers of terrestrial species per unit area in humid tropical, well-drained, though not necessarily fertile, soils. As soon as limitations occur, the number of species tends to decrease. However, harsh conditions do not always imply very low diversity, as the floristic diversity of soils developed on serpentine rocks shows. Furthermore, high ecosystem productivity, for example in estuaries, does not mean high biodiversity, and the eutrophication of surface waters is known to lead to reductions in species numbers. In well-drained parts of the humid tropical rainforest in the Colombian Amazon, higher numbers of tree species are found on successively older geological terrains. This means that protecting a rainforest site just for a single cycle of say 200 years is not long enough to ensure maximum biodiversity. Conservation of biodiversity implies long time scales.

That is not to say that species from sites of high biodiversity are to be valued more than those from low-diversity sites, only that the risk of loss of unique genetic material is much greater if there is destruction of high-diversity site communities. Furthermore, the role of a single tree species in a complex 300 species rainforest ecosystem is almost impossible to unravel. Therefore biodiversity as a vulnerable resource should not only be considered at the species level, but also at the community level. A minimal surface area is required for the functioning of plant and animal communities, which is specific for each species. Retaining biodiversity as a natural resource requires conservation of sufficiently large areas of life communities at as many habitats as possible over a long time.

Human land use affects biodiversity through the destruction of entire ecosystems, through forest clearing, the disturbance of nutrient cycles (eg through excessive fertilizer application or removal of ground cover) and damage to system components (eg loss of the topsoil). Biodiversity can be conserved in three ways:

- (1) Strictly limit agriculture to areas away from natural communities; intensify agriculture on those lands most suitable, and leave the rest for nature (spatial differentiation). This means that natural communities which occur on land suitable for agriculture are given up for ever.
- (2) Alternate agricultural land use with periods of natural vegetation (temporal differentiation); this is often harmful to ecosystem components.
- (3) Design mixed types of land use (agroforestry, silvopastoral systems) which combine agricultural production, usually at low

levels, and conservation of some ecosystem components (agroecological differentiation).

Making decisions on sustainable land use

In order to assess what levels of disturbance and nutrient and energy extraction are acceptable in agroecosystems without endangering sustainability we again have to refer to specific time and spatial scales. In contrast to the biophysical production factors considered here (Figure 3) human population displays an exponential growth rate expected to level off only after 2100. As a result of the more than proportional growth in the demand for agricultural products the coming century will see an even greater exponential increase in the extraction of nutrients and energy from agroecosystems. Because the scope for area expansion is rather limited worldwide, most additional production will have to result from increased yields per time–area unit. The efficiency of input use at high production levels, however, will mitigate some of the exponential increase.

In practical terms sustainability must be translated into a set of boundary conditions defining acceptable levels of outflows of matter and energy from the agroecosystem. In other words, sustainability nearly always means limits placed on production potential, whether spatial (decisions on limiting the area and land types taken into production) or temporal (limiting annual outputs). Acceptability implies that an arbitrary limit is set by a (group of) decision makers, whether farmers or governments. Here, time and spatial scales interfere as well: what is acceptable to farmers in view of their objectives that do not extend beyond the farm and the next generation may not be acceptable to an entire nation. Decision making is also subject to matters of time scale. Ideally, one would want to postpone a decision indefinitely until all information on the effects of land use are available; in practice, however, many decisions on sustainability must be taken in the short run with insufficient knowledge. Furthermore, decisions at each level affect those at other levels (EC price policies, farm-level pesticide application).

The concept of sustainability can be used in two ways: to evaluate existing systems and to design new land use systems. Taking decisions about future land uses requires consideration of different alternatives. For each land unit it has to be established which combination of spatial, temporal and agroecological differentiation is most sustainable in the long term, and offers optimal resilience to external threats. This leads to quantified boundary conditions that can then be used in interactive goal planning so that trade-offs between different, competing goals can be made visible. However, these planning procedures have so far failed to incorporate processes operating on a longer time scale, such as the effects of changing environmental conditions (climatic change, nutrient inputs from volcanoes, or flooding). The conservation of low-resilience resources like topsoil and biodiversity is also not made an explicit boundary condition. Furthermore, the long-term and spatial effects of land use on natural resources are rarely if ever considered in land use scenarios.

Conclusions

Ideally, and over non-geological time scales, ecosystems are sustainable

if human interference is absent or negligible, such as in shifting cultivation. A central issue for future research is to establish whether agroecosystems are sustainable if they display similarity in internal resource flows and positive and negative feedback mechanisms to those in natural ecosystems. If this is so, sustainable agroecosystems are those in which the resource flows remain as close as possible to threshold values determined by natural patterns.

Sustainability itself is a time-linked concept. As we approach time scales of more than thousands of years no ecosystem is ever sustainable, even if it seems that cycles of sustainability or punctuated equilibrium appear.²⁷ Sustainability, although its underlying processes are scale related, may even be said to display fractal behaviour, irrespective of scale. What is catastrophic on a small scale may be part of the system on a larger scale, or, conversely, what seem stable trends over long periods are punctuated by fluctuations if one examines the system in detail. This leads us to the following conclusions:

- (1) Sustainability in agroecosystems has to be defined with reference to specific hierarchical levels and scales of space and time; it refers to the balance between natural degrading processes and human interference in the agroecosystem on the one hand, and restorative natural processes and protective human management on the other.
- (2) Sustainability can only be evaluated if higher hierarchical levels than the system under consideration are also taken into account.
- (3) Production, input/output and stability are intrinsic aspects of sustainability within one scale; resilience is the most important aspect describing the impact processes at a higher scale.
- (4) Natural resources with least resilience are: soil nutrients, topsoil and biodiversity; priority should be given to conservation of these resources in any decisions on future land use.
- (5) External processes such as climatic change and natural hazards are so dynamic that scenarios for sustainable land use at the local and regional level should not be made for more than 200 years ahead.
- (6) Agroecosystems can be characterized according to productivity and magnitude/speed of resource flows, and should be ranked on a 'sustainability scale' as well as a productivity scale.
- (7) Decisions on sustainable land use have to be taken using alternative scenarios at different hierarchical levels of time and space, including specific sets of boundary conditions acceptable to different groups of users (farmers, extensionists, conservationists, politicians) in their spatial and temporal perspective.

²⁷S.J. Gould, *Time's Arrow, Time's Cycle*, Penguin, Harmondsworth, UK, 1987.