Working Paper

Environmental Indicators and Their Applications (Trends of Activity and Development)

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(Trends of Activity and Development)

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Foreword

Environmental problems are complex: the same problem may have several causes and the same stress may cause several problems. An environmental indicator is a number that is meant to indicate the state of development of important aspects of the environment. Strictly speaking, the term "indicator" refers to a specific number along the time or space dimension. A set of indicators should give information on development, environmental quality, and environmental policy.

The present paper includes an overview of the state of environmental indicators (Part 1) and application of the response function method to the indicators issue (Part 11). The main goal of this paper is to give information on further development of environmental indicator activity. As the application of the environmental indicators is of special interest to IIASA's Projects entitled " Forests Resources, Environment, and Socioeconomic Development of Siberia" and " Modeling Land Use and Land Cover Change in Europe and Northern Asia" the paper is mainly focused on the formation of indicators for the land-use and forest studies.

Part 1:

Overview of past and present trends of activity

1. Introduction

In the last three decades, many indicators and statistical approaches for interpreting and presenting information on the state-of-the environment have been developed. During this period man has collected vast quantities of data and information about himself and the physical and biological world around him.

Technology provides much better possibilities today than before for both collection, compilation, analysis, presentation and dissemination of data and environmental statistics. Key words are automatic monitoring, remote sensing, databases, electronic data communication and analysis tools such as statistical packages and geographical information systems. Tools for better presentation in the form of graphics and maps are also widespread. In spite of this, it seems that an expected gain in better *information* has not been reached. We have got a situation where we have an affluence of data and statistics, but where we still lack relevant information. This is in particular true for information on the state of the environment, and is probably on of the reasons why *environmental indicators* have been put in focus in many countries and international organizations.

Environmental management efforts around the world are measuring and reporting the status and behavior of the environment. Given the complex physical, chemical, and biological interactions contained within natural and cultural environments, the question of how society is to measure the environment and understand its status and behavior is a topic that is receiving increasing attention. A major element in the design of systems to measure the environment and provide the information necessary to make management decisions regarding the environment's desired status and behavior. Of all the naturally and culturally related environmental variables that could be measured, which one, or several can we, as a society measure, evaluate, and understand? Which variables are most representative of those aspects of the environment that we value and want to manage?

While many of the decisions that have to be made require very site-specific information about the behavior of specific physical, chemical, and biological variables (indicators), the status and behavior of general environment quality must be assessed over the entire jurisdiction of the management effort and over many years. Monitoring systems working on these vast time and space scales generally use some form of statistics to make inferences about environmental quality from samples extracted at representative locations in the environment.

In the field of environmental reporting it is very difficult to find examples of quantitative information on the environment's status and behavior regularly reported to the public, their elected representatives, and professional environmental managers in an easily understood format.

Increasing concern about the environmental issues that threaten the global commons is evident throughout today's media. The known and anticipated effects of various environmental problems-global climate change, stratospheric ozone depletion, habitat destruction, and species extinction, to name a few of the most pressing - are widely reported. Despite growing concern about these and other problems, however, we are limited in our ability to adequately assess ecological status and to detect trends and changes in environmental condition.

Many organizations worldwide have long recognized the need for better information on the state of the environment. To address this need, several international groups are examining the use of "indicators" to describe and evaluate ecological condition. When properly implemented, such ecological indicators can be used to assess ecosystem status and trends, gain a broader understanding of ecosystem processes, anticipate emerging environmental problems, and address national and international monitoring, regulatory, and policy needs.

Clearly, the study of environment indicators, defining and establishing the means of measuring the health of the environment, is of great importance. For most of our history, we *Homo Sapiens* have been flying blindly into the future, not knowing our relationship to our life-supporting environment or our principal role in destroying it. Only recently, in the last 20 years, have we made major progress in furthering such understanding. Now many of us worldwide recognize our interdependence, not only with each other but with all other plant and animal life, and our dependence on the air, water, soil, and sun. The development of environment indicators has contributed much to the growing enlightenment. Today, even leading decision makers in government and business appear to recognize the interconnections and identifying themselves as environmentalists.

However, society has a long way to go to develop adequately the knowledge and commitment necessary to cope with the accumulating impacts of human activities on the environment. The environmental movement's current emphasis on sustainable development with its concern for the quality of life of future generations-for intergenerational equity-is indeed encouraging.

All these and many other problems are discussed in the two volume proceedings of International Symposium on Ecological Indicators in 1990.

2. Goals and Definitions

Discussions of environmental indicators issues must first address how environment indicator information is to be used. Whether the user group is the scientific, policy, or regulatory community, common priorities do exist. There is a need to assess and document the condition of ecological resources, particularly to establish baseline conditions for current ecosystem status. Methods to detect and interpret trends in ecosystem status, and early warning of significant long-term change in ecological condition are needed. All groups desire the ability to predict emerging environmental problems before they become widespread or irreversible. It is also important to be able to effectively communicate information about ecological effects, status, costs, benefits, alternatives, and tradeoffs to the scientific community, the public, and policy makers. Environment indicators are one approach addressing all of these needs.

In addition to these common needs, the scientific community has unique needs which the use of indictors can serve. Regardless of the specific issue under investigation, the ability to understand environmental systems and processes and to establish cause an effect relationships are universal factors driving scientific interest and endeavors. These qualities require that the indicators and their applications have a sound scientific foundation. Indicator research can help to establish more complete understanding about ecosystems and serve as a stimulus for advancing ecological theory. There is still much to be learned abut the structure and function of ecosystems, and about ecosystem mechanisms and processes. The variation among ecosystem types makes these tasks much more complex. New information on all advancements in the ability to use indicators to accurately predict ecosystem response to individual and associated environmental pollutants, stressors, or actions is needed.

The policy community also has unique requirements that the use of indicators can address. While the scientist's first concern is advancing the knowledge base, the policy maker's key concern is better information for decision making. Environment indicators are needed to help policy makers make better decisions. Relevant information interpreting ecological condition is needed to improve public awareness, guide regulatory approaches, and inform administrative action. Indicator information is expected to help assess which ecosystems are likely to be at risk, both currently and in the future. Environment indicators are needed to evaluate the success of current policies and programs and progress toward reaching environmental goals. This user group requires timely information. Environment indicator information must be available at the time a decision must be made in order to be considered.

It is obvious that the need for a simple and general overview of the development in the state of the environment has led to work on environmental indicators in national as well as in different international organizations. The most suitable and effective definition of environmental indicators from our point of view was proposed by K.H. Afsen and H. V. Saebo (1993):

An *environmental indicator* is usually defined as a number indicating the state and development of the environment or conditions affecting the environment.

An environmental *indicator* is a number that is meant to indicate the state or the development of important aspects of the environment. An indicator without a unit of measurement is an *index.* An index is often constructed from several indicators weighed together to capture the total impact on an aspect of the state of the environment. A *leading* indicator to an environmental indicator, is an indicator that gives early warning of the development in the environmental indicator. More constructive definition of the environmental index is based on Lefebver (1983) approach: an environmental quality index is an algorithm that express a measurement of an assessment of the environment's qualitative state. it is a simplified expression of a complex combination of several factors and its relevance depends on its reliability and the quantity of information it provides. The final result can be a unique symbol or a simple combination of numerical and alphanumerical variables.

We can draw a parallel to economic indicators. The score of macroeconomics policy is often measured by aggregated economic indicators such as Gross Domestic Product (GDP), Net National Income, industrial production, unemployment rates and the balance of the current account, to mention a few. Thus, it is clear that the state of the economy is not described by a single indicator. Rather, it is the indicator set as such that gives a rough indication of the current state of the economy. Similarly, a set of environmental indicators is meant to give a picture of the state of the environment.

Both in the case of the economy and the environment, the indicator is meant to give information in excess of what is directly measured or observed, i.e. the *parameter* value or statistical information. Thus, an indicator is seldom presented as a single datum, but it should be put into some context from which it is possible to infer what is indicated. The statistical data can for instance be a measurement of the SO_2 concentration at a specific time and place. In order to indicate something about air pollution, it can be supplemented with information on a recommended threshold level, or a time series of measurements sufficient for giving an indication of the air quality. Often the data must be acceptable as an indicator. Maps are often employed when geographical distribution is of importance.

3. Requirements and Uses

Along with the requirements of being effect oriented and not too uncertain or controversial, there are further properties we ideally would like the indicator set and the individual indicators to have. Very briefly they are related to the following items (Afsen and Saebo, 1993):

General overview. The set of indicators should give an impression of some of the more important aspects of the state of the environment may be hard to interpret by itself and in isolation. To provide points of reference in time and space, the indicator set should preferably be comparable with indicators in other countries and should contain long time series.

Sensitivity. The indicators should be sensitive to changes in the state of the environment. However, it is important to be able to identify man-made impacts on the environment from natural variations. One way of separating man-made and natural variations may be to collect time series from before the industrial revolution. Unfortunately it will rarely be possible to construct such long time series, But still the length of the time series is an important aspect in the choice of indictor. Also, the indicators can focus on marginal environmental areas, where changes are most likely to be noticed first.

Easy interpretation. The indicators should be as self explanatory as possible. At least, interpretation of the indicators should not require advanced knowledge of disciplines like for instance biology, earth sciences or economics.

Data. Data underlying environmental indicators should be easily accessible and available at a reasonable cost.

The Ott's (1978) review of the literature has identified six basic uses of environmental indicators. The uses listed here are not necessarily unique to given indicators, because indicators sometimes are applied for more than one purpose. Nevertheless, one can find examples in the literature where an indicator has been developed or proposed for each of the following purposes:

- Resource Allocation Indicators may be applied to environmental decisions to assist managers in allocating funds and determining priorities.

- Ranking of Locations Indicators may be applied to assist in comparing environmental conditions at different locations or geographical areas.

- Enforcement of Standards Indicators may be applied to specific locations to determine the extent to which legislative standards and existing criteria are being met or exceeded.

- Trend Analysis Indicators may be applied to environmental data at different points in time to determine the changes in environmental quality (degradation or improvement) which have occurred over the period.

- Public Information. Indicators may be used to inform the public about environmental conditions.

- Scientific Indicators may be applied as a means for reducing a large quantity of data to a form that gives insights to the researcher conducting a study of some environmental phenomenon.

- In each of these applications, the indicators helps convey information about he state-of -the-environment. Because the questions being asked are different in each application, however, the indicators may differ in terms of the variables included, the basic structure, and the manner in which it is applied. Because different users have different data-reporting needs, identification of the users should be a critical part of the development and application of any environmental indicators as suggested by Coate and Mason (1975): "It is absolutely critical that the user be identified. The scientist, administrator, elected official, and general public cannot usually be satisfied be the same environmental measure. the administrator needs to see the resource allocation implications and the scientist needs to see the cause and the effect implications. who the user is will also affect geographical or political aggregation of data and the decision to highlight or obscure inter jurisdictional comparisons."

Another important question is the criteria for indicator selection. Short list of criteria for the selection of environmental indicators was proposed in recent OECD (1993) report. From the point of policy relevance and utility for users, an environmental indicators should:

- provide representative picture of environmental conditions, pressure on the environment or society's response;

- be simple, easy to interpret and be able to show trends over time;

- be responsive to changes in the environment and related human activities;

- provide a basis for international comparisons;

- be either national in scope or applicable to regional environmental issues of national significance; and

- have a target or threshold against which to compare it so that users are able to assess the significance of the values associated with it.

From the point of analytical soundness, an environmental indicators should:

- be theoretically well founded in technical and scientific terms;

- be based on international standards and international consensus about its validity;

- lend itself to be linked to economic models, forecasting and information systems.

From the point of measurability, the data required to support the indicator should be:

- readily available or made available at a reasonable cost/benefit ratio;

- adequately documented and of known quality; and

- updated at regular intervals in accordance with reliable procedures.

More accomplished approach to indicators selection strategy was proposed by US Environmental Monitoring and Assessment Program (EMAP). Identifying values and policy relevant, assessment questions represents the first step in the ongoing process of selecting indicators and developing strategies for their evaluation and use (Table 1). As they are identified, indicators must be conceptually related or linked with the social value and must also provide information to address assessment questions. Before an indicator can be implemented, however, it must be explicitly linked with the value. The next step in the EMAP indicator strategy was, and is, evaluating the literature on important condition indicators for various ecological resources. To identify initial, specific indicators as the start of the program, scientists, engineers, and public policy analysts evaluated candidate indicators that has been proposed for monitoring over the last three decades. Draft criteria for indicator selection were formulated and reviewed, and a final set of criteria was developed. Each resource group judged its candidate indicators against these criteria to identify a set of indicators for further testing and evaluation. Comments from peer reviewers and from EPA's Science Advisory Board were used to refine the indicator sets and the EMAP indicator development strategy; part of considering condition indicators also included identifying associated stressors. The same process is to be followed when proposing new indicators to measure.

Taking into account these circumstances we will restrict our consideration in the future only to the scientific research users.

4. Ecosystems Health and Environmental Indicators

A central theme of the 1992 Report of the WHO Commission on Health and Environment is that "the maintenance of health should be at the center of concern about the environment and development". This theme is reflected in the recommendations of the United Nations Conference on Environment and Development (UNCED) relating to the development of national plans for sustainable development. UNDP has launched a global capacity building program (Capacity-21) aimed at promoting and supporting the preparation and implementation of these plans. The health sector is to play an active and key role in developing the health and environment sections of the plans. The WHO Director-General's Council on the Earth Summit Action Program for Health and Environment, which met in January 1993, concluded that the perpetration of such plans should be a matter of the highest priority and recommended that WHO facilitate the process by organizing specific country initiatives to demonstrate how such plans should, in fact, be developed and implemented. It is tin the interest of health that the national plan(s) for sustainable development reflect the national health development strategies and clarify the role of the health sector in the health-environment considerations into the other relevant development sectors.

Following R. Costanza (1992) ecosystem health is a bottom line normative concept. It represents a desired endpoint of environmental management, but the concept has been difficult to use because of the complex, hierarchical nature of ecological systems. Without an adequate operational definition of the desired endpoint, effective management is unlikely.

Existing definitions of ecosystem health can be summarized as:

1. Health as homeostasis
2. Health as the absence of disease
3. Health as diversity and /or complexity
4. Health as stability and/or resilience
5. Health as a vigor and/or scope for growth
6. Health as balance between system components

All of these concepts represent pieces of the puzzle, but none is comprehensive enough to adequately serve as a measure of system health. A health system must be defined in light of both its context (the larger system of which it is a part) and its components (the smaller system that compose it). The degree of organization of this hierarchical system, adjusted to incorporate its stability and vigor, can form the basis for a general indicator of its health.

All complex systems are, by definition, made up of a number of interacting parts. In general, these parts, or components, vary in their type, structure, and function within the whole system. Because of this, the behavior of these systems cannot be summarized by the addition of the behavior of each individual part.

In its simplest terms, then, health is a measure of the overall performance of a complex system, built up from the behavior of the parts of the system. Such measures of system health imply a weighted summation over the component parts, where the weighting factors incorporate an assessment of the relative importance of each component to the functioning of the whole system. This assessment of relative importance incorporates values, that can range from subjective and quantitative to objective and quantitative, as more specific knowledge about the system under study is gained.

Indicator of ecosystem health is thus a comprehensive, multiscale, hierarchical measure of system stability, organization, and vigor. What does this mean in practice? To quantitatively operationalize this concept a heavy application of systems modeling will be required.

5. Sustainable Development

As was noticed by D. J. Rapport (1992) The "third wave" in the development of environmental indicators refers to the need for seeking truly integrated measures of ecological transformation within the context of soci-economic and cultural change.

This "third wave", or more aptly, distant "swell," is being propagated by the politically motivated quest for indicators of " sustainable development." This gives rise to the impetus to seek conductivity between ecological considerations an economic and social factors: to define a larger and proper context for assessing the health of the environment.

The talk of developing holistic measures of the sustainability of regional ecosystems poses complex challenges. The task might begin with the "simple" question: what is it that humans are attempting to sustain? Is it the "stage" upon which the subsequent generations will enact their own play. If so, the development of environmental indicators must be closely linked with information coming from many other domains including demographic and social-economic data. Indicators of "sustainable development" need to track not only the health of ecosystems per se but also social measures, for example investment in education for future generations and efficiency measure, such as the efficiency in the use of renewable energy.

Such considerations bring to the fore the overall context in which environmental indicators are being sought. This context is defined by the factors determining global environmental futures: a likely doubling of global populations; sharply rising expectations for material betterment in third-world countries; rising gaps between rich and poor nations; increasing stress from human activities; and threats of rapid global climate warming, depletion of the ozone layer, massive rates of biological extinction, and the like. In this context, indicators such as "greenhouse" gas emissions are of increasing importance since they interface with changes in both the biological side of the equation (depletion of forests for example) and the economic side (the consumption of fossil fuels, biomass, etc.). Thus the only suitable background for elaborating indicators of sustainable development is a system analysis approach.

Given the above notice there was proposed by W. Y. Niu and others (1993) conceptual framework for the analysis and evaluation of sustainable development follows a spatial systems approach. In this context, a *spatial system* refers to a complex physical-societal system, which has a distinct geographic space with specific boundaries (either natural or artificial). The scale of spatial systems may vary widely, ranging from local to global, thereby giving rise to nested hierarchies of spatial systems. According to this conceptual framework, as summarized in Fig. 1, a spatial system comprises five interconnected aspatial subsystems or subsets with respective operational dimensions. These are: (1) life-support subsystem (per capita carrying capacity of resources), (2) well-being-support subsystem (productivity of the economy), (3) process-support subsystem (stability of development), (4) environmental-support subsystem (assimilative capacity of the environment), and (5) intelligence-support subsystem (adjustability of management). these subsystems and their corresponding operational dimensions are important elements in analyzing sustainable development at different spatial levels-local, regional, national, or global.

For our aim the most interesting point here is the need for measures of environmental -support subsystem quality.

The basic premise is that the organization of an ecosystem represents a tradeoff between the imperatives of survival and the second law of thermodynamics which necessitates the degradation of energy. Ecosystem organization tends to increase degradation of energy. Measures of ecosystems. organization should therefore reflect energy usage and degradation in ecosystems. Measures of energy utilization in the ecosystem food web and by the ecosystem are presented.

Integrity of an ecosystem refers to its ability to maintain its organization. Measures of integrity should reflect the organizational state of an ecosystem. Ecosystem organization has two distinct aspects, functional and structure refers to the interconnection between the components of the system. Measures of function would indicate the amount of energy being captured by the system and the way in which it is being degraded (for example, respiration vs. evapotranspiration). Measures of structure would indicate the way in which energy is moving through the system. for example, measures of the amount of recycling in the ecosystem, the effective tropic levels of species, and the average specialization of the resource niche all reveal something about how energy is being used in the ecosystem.

A well known base to construct the needed measure is the concept of carrying capacity as was pointed out by D. I. Carey (1993): "the concept of carrying capacity provides a framework for integrating physical, socioeconomic and environmental systems into planning for sustainable environment." The concept of carrying capacity is derived from the idea that an organism can exist only within a limited range of physical conditions. Plants and animals require a minimum amount of energy and critical materials, a certain range of temperatures, and can withstand only certain concentrations of chemicals. The availability of suitable conditions for living determines the number of organisms that can exist in an environment.

The concept of carrying capacity can be applied to both plant and animal populations ad has been used in forestry management, wildlife ad fisheries management, recreation and transportation planning, archaeological and anthropological studies, and water-quality and air-quality management. The concept is implicitly used by herdsmen when they manage the size of their herds to prevent overgrazing. Carrying capacity in this context depends on highly variable factors, such as the amount and temporal distribution of annual rainfall, temperatures and so forth. Since fluctuating environmental factors cannot be predicted, carrying capacity is usually estimated at conservative, sustainable levels based on experiences which generally cannot be explicated.

6. International Activity

A number of countries and international organizations have started work on the development of environmental indicators. The work varies with respect to target group(s), to which part of the environment and sometimes natural resources the indicators are meant to describe, and how the indicators are grouped. The set of indicators therefore varies a great deal, and it is difficult and perhaps unreasonable to try to characterize one set as better than another.

Nevertheless the interest in sustainable development and growing public concern about environmental threats have stimulated governments to re-examine their capacity to assess and monitor the state of the environment and detect changing conditions and trends. Pressures are also growing for measurement of performance, i.e. evaluation of how well governments are doing in their efforts to implement their domestic environmental policies an international commitments. Thus, environmental indicators are increasingly seen today as necessary tools for helping to chart and track the course towards a sustainable future.

In May 1989, the Organization for Economic Co-operation and Development (OECD) meeting at Ministerial level called, inter alia, for a next-generation work program on environmental economics that would integrate environment and economic decision-making more systematically and effectively as a means of contributing to sustainable development. In July 1989, the Paris Economic Summit reinforced this; in July 1990, the Houston economic Summit, in its declaration, reiterated its call upon OECD to carry forward work on environmental indicators

"We ask the OECD within the context of its work on integrating environment and economic decision-making, to examine how selected environmental indicators could be developed".

Excerpt from G-7 Economic Summit Declaration, Paris, July 1989.

"We encourage the OECD to accelerate its very useful work on environment and the economy. Of particular importance are the early development of environmental indicators and the design of market-oriented approaches that can be used to achieve environmental objectives."

Excerpt from G-7 Economic Summit Declaration, Houston, July 1990.

The OECD response:

The work carried out by the OECD focuses on sets of indicators to be used for the integration of environmental and economic decision-making, at national and international level. These indicators can also be valuable in communicating with the public.

In particular, environmental indicators should serve to inform the ongoing process of policy dialogue among countries and to lay the basis for international co-operation and agreements. As such, environmental indicators may also be seen to parallel the role of economic indicators used in economic policy co-ordination by the OECD countries. Because indicators need to be viewed in a dynamic context, they are subject to revision in order to reflect the changing nature of policy perspectives and of public perceptions regarding the seriousness of different environmental problems.

Sets of indicators are series selected from a large data base with a synthetic meaning an specific purpose. Consequently there is no universal set of environmental indicators; rather, there are sets of indicators responding to specific conceptual frameworks and purposes.

Three types of indicator sets are currently under development at OECD in order to contribute to:

i) measurement of environmental performance with respect to the level and changes in the level of environmental quality, and the related objectives defined by national policies and international agreements. Summary indicators of environmental performance may also be particularly valuable in responding to the public's "right to know" about basic trends in air and water quality and other aspects of their immediate environment affecting health and well being;

ii) integration of environmental concerns in sectoral policies. This is done through the development of sectoral indicators showing environmental efficiency and the linkages between economic policies and trends in key sectors (e.g. agriculture, energy, transport) on the one hand, and environment of the other;

iii) integration of environmental concerns in economic policies more generally through environmental accounting, particularly at the macro level. Priority is being given to two aspects: the development of satellite accounts to the system of national account, and work on natural resource accounts (e.g. pilot accounts on forest resources).

As first step in this direction the publication of a preliminary set of environmental indicators by which to measure environmental performance. It is published together with the 1991 OECD Report on the State or the Environment, which gives a more complete picture of environmental conditions and trends, particularly for issues not yet amenable to statistical analysis (e.g. air toxics, pesticides).

This preliminary set of indicators is patterned on the outline of the OECD Report on the State of the Environment. It comprises 18 environmental indicators per se, followed by 7 key indicators reflecting economic and population changes of environmental significance. It includes indicators of environmental performance, some relating to environmental quality itself (e.g. river quality, nature protection), some to national environmental goals (e.g. sustainable use of the water resources, controlling waste generation), and some to international environmental agreements and issues (e.g. SOx emissions, trade in forest products).

Further work on this matter will follow the recommendations expected from Environment Ministers of OECD countries meeting in January 1991. At present, it is envisaged:

-- to ensure Member countries' commitment to the development of a commonly agreed core of set of environmental indicators;

-- to use this set of indictors in order to better assess countries' environmental performance;

-- to encourage Member countries to supply better environmental data.

Indicators of environmental performance should be developed with reference to environmental quality, national goals and international agreements. Their design should also be compatible with environmental reviews, similar to the traditional OECD reviews of the economic situation energy situation of Member countries.

The development of these environmental indicators will require a second generation of environmental statistics and information, with:

-- expanded geographic coverage;

-- more economic data relating to the environment (e.g. environmental expenditures, trade data);

-- more aggregate and summary information.

Above all, this will require better data rather than more data, so as to improve the quality of many existing statistics and their international comparability and to fill the major gaps in environmental information. Progress can be achieved through better use of various techniques, such as: monitoring, accounting, remote sensing, geographic information systems, and networking of environmental information systems.

An attempt to produce composite environmental indicators was made by A. G. Hoare (1993). In his paper he tried to move the idea of Hope, Parker and Peake (1992) towards an international and global scale of reference.

R. B. Miller and H. K. Jackson (1992) exploring the human components of global change. In particular they pointed out that the problem of scale and scope is not confined to research on global change, but will increasingly be encountered through-out the social sciences. The traditional mode of organization for social science research is incapable of dealing with this type of research need. To understand global change, for example, social scientists must expand the spatial, temporal, and disciplinary scope of their research. This will require not only a multinational focus and multidisciplinary analysis, but also both multinational and multidisciplinary participation in the research effort.

More accomplished survey on the international activity on the indicators issue is given in the recent Environment Assessment Technical Report " An Overview of Environmental Indicators: State of the art and perspectives", UNEP 1994.

To accomplish this, the environmental sciences will require new institutional structures which can organize and manage such diverse components of large scale research problems as data collection for environmental indicators, their calibration and analysis, and the training of new researchers. These structures must also be capable of integrating these activities of researchers from variety of countries and disciplines.

In assessing the readiness of the researchers to enter this field, the first issue to consider is the theoretical base for research on environmental indicators of global change. Experience clearly indicates that research will not be successful unless there is an adequate theoretical foundation for the work that is to be done.

7. Structure of Environmental Indicators

The process of the environment impact assessment according to L. W. Carter and L. G. Hill (1979) involves five activities. The first is an understanding of the legal bases and procedural requirements for the process. Second is a description of the environmental setting where the proposed action is to take place. Assessment variables, or more simply, variables, refer to those characteristics of the environment used to describe the baseline environmental setting an upon which impacts may occur. The third activity in the process, and the one which requires the greatest scientific application of technology, is impact prediction and assessment. The impacts of each of the alternatives being evaluated on each of the variables should be predicted and interpreted. The fourth activity involves the aggregation of impact information on each alternative. Based on this aggregated information as well as technical and economic considerations, the alternative to become the proposed action is selected. The final activity involves the preparation of an environmental impact assessment report (EIA) describing the procedure and findings.

Appropriate selection and use of variables is an important component of the environmental impact assessment process. Variables represent key features of the activities involving description of the environmental setting, impact prediction and assessment, and selection of the proposed action. To provide a structure to the variables considered, the environment can be compartmentalized into physical-chemical, biologic, esthetic, and socio-economic features. For example, the variables can be grouped into the Environmental Quality (EQ), Social Well-Being (SWB), and Regional Development (RD) accounts. The EQ account primarily addresses the natural environment and includes physical-chemical, biological and esthetic variables; the SWB an RD accounts are oriented to the man-made environment and include socio-economic variables.

To provide a structure for considering and selecting the variables presented in Fig. 2 four categories were chosen, namely, terrestrial, aquatic, air, and human interface. The terrestrial and aquatic categories include physical-chemical and biological variables; the air category includes physical chemical variables; and the human interface category includes esthetic variables along with noise an historical and archeological resources. These categories of the environment were used in a water resources environmental impact assessment methodology (Solomon, et al., 1977). Each variable included is grouped into either the terrestrial, aquatic, air or human interface categories; and described in terms of measurement, prediction and evaluation considerations.

Another approach to selecting the environmental indicators and variables was described by D.B. Tunstall (1979), a detailed list of it is shown in Fig. 3.

A hierarchical arrangement of indicators was developed by R. F. Noss (1990) involving the monitoring of biodiversity. His biodiversity hierarchy concept Fig. 4. suggests that biodiversity be monitored at multiple levels of organization and at multiple spatial and temporal scales.

From these three examples it is clear that the general formation of the indicator of environmental quality is a very complicated problem.

The procedure of development of single indicators through a local sequence from the identification of candidate indicators through literature review and the techniques, through to core indicators is shown in Fig. 5. This idea was proposed by C. T. Hunsaker and D. E. Carpenter (1990) for EMAP-Arid project.

A similar approach was proposed by the Mitre corporation in it's report to the USA Council on Environmental Quality. It outlines eight types of indices (see Fig. 6) that were expected to directly measure important national goals - air, water, solid waste, erosion potential, noise, radioactivity, urban parks and housing. The intent of the report was to specify a mode for indicator development and plan for eventual data collection and processing.

In 1975 the EPA Program Evaluation Division of the Office of Planning and Evaluation prepared the first report of the environmental measures project *Analysis and Applications of Environmental Quality Indicators.* This conceptual report outlined the uses of specific data for air and water measurements and ranked environmental data for use as indicators. (See Fig. 7).

At the same time G. C. Thom and W. R. Ott (1976) developed Standardized Urban Air Quality Index (SUARI). The overall process by which SUARI was developed is illustrated in a flow diagram (Fig. 8) . In the top half of the diagram, the indicator classification system was applied to the indicators in the literature and those in common use. Using this system, the most commonly occurring characteristics of the indicator used by air pollution control agencies, or the "preferred" indicator characteristics," were readily identified. In the bottom half of the diagram, the comments from the indicator users and non users, along with information gained from the three-state case study, were evaluated to arrive at the 10 criteria for a uniform indicator.

In the framework of our consideration, calculation of an environmental indicators is viewed as consisting of two fundamental steps: (1) formation of the sub-indicators for the variables used in the indicators and (2) formation of the aggregation rules of the sub-indicators into the overall indicator.

The overall process-calculation of sub-indicators and aggregation of sub-indicators to form the indicator-can be illustrated in a flow diagram (Fig. 9). In this process, the "information" contained in the raw data (environmental measurements) flows from left to right and is reduced to a more parsimonious form. Some information may be lost; however, in a properly designed indicator, the information loss should be of such a nature that it does not cause the results to be distorted or ultimately misinterpreted.

In the next sections we will consider the problems of modeling and data base formation in the environmental indicators framework.

8. Environmental Modeling

One of the main parts of environmental indicators formatting is receiving the information on the most important variables of the state of ecosystem and knowing the ecosystems response on the changing of state and driving variables. Dynamic models allow better understanding of complex relationships. Their structure can be communicated to achieve a common understanding within a research group. They may show unexpected behavior which also helps in understanding problems. Some types of models tend to correct mistakes in data, in particular feedback models.

Models are often cross disciplinary. Specialized scientists tend to reject the transgression into their area by model building group. They tend to defend their turf; modelers tend to underestimate the value of the knowledge available in the specific fields.

Many problems exhibit complex structures and aggregated characteristics. Land-use examples for complex structures are 1): the relationships between demand for land, suitability of land for a purpose and resulting land use change, 2): the manifold factors in the preservation of biodiversity, or 3): the global structures involved in weather, climate and climate change.

Such structures can adequately be depicted with aggregated dynamic feedback models. Often the dynamics are similar through large regions, e.g. due to national laws or in continental build up of ozone during high pressure regimes. In the extreme such spatially extended variables can be global, as for example in the CO_2 increase. But locally the dynamics are *modified* by spatially varying factors, e.g. altitude, steepness, soil type, by administrative regulations or by the vegetational changes in the case of CO_2 increase.

The feedback's and interactions among the components of the overall environmental system are such that we cannot expect to influence one without affecting others. Models are used to make sure that controls are indeed likely to have the consequences that are desired and that they will not have second-order effects that defeat the original purpose.

In particular, the linkages between media need to identified, formulated, and then included in the appropriate models. Once included, it is necessary that the predictions be tested against observations obtained independently. In this regard, it is important that any model should be both verified by comparison against data and validated as a result of examination and acceptance by appropriate agencies.

It is relevant to distinguish between statistical and mechanistic models: *Statistical models* are based on data; they express the relationship between effects and possible causes, an so emphasize the most significant correlations among properties represented in the available observations. They cannot address processes that are not observed. Moreover, in concept they express the statistical features of the data on which they are based an are hence most suitable for use in interpolating among the basic data set. In concept, they should not be considered suitable for application to situations that differ from those of the data on which they are based. *Mechanistic models* are constructed by integration of descriptions of the relevant processes. They are then tested against data made in a variety of conditions, so as to test each parameterization individually and to test their interactions. These models are far more advanced in that they require understanding of the links between causes and effects, rather than beliefs that such links should exist.

Ecological modeling may be considered the most advanced form of EIA (environmental impact assessment). A relation between the most important variables of the state of the ecosystem (state variables) and the external (driving) variables in expressed in mathematical terms. Once the model has been developed, it means that it has been calibrated as well as validated (the ability of the model to match independent observations has been found and possibly expressed numerically as, for instance, a standard deviation of the model), and it is possible to make simulations. Various scenarios are tested and compared with respect to the environmental impact on the ecosystem, for instance. A proper model is therefore a powerful tool in environmental management, and the results may be applied to set up environmental management plans.

Many models developed during the last two decades may be adjusted to study many crucial environmental questions. Even models of long-term successions have been developed that can simulate changes due to pollution. Such succession models are, however, very complicated, because they must contain parameters for growth of many species. Furthermore, models do not reflect the flexibility found in a real ecosystem, where the species do not have fixed parameters but may change them in accordance with adaptation processes. Therefore, we need to develop models that take into consideration the regulation mechanisms and the feed-back mechanism of the real ecosystem.

New generation of models is based on introduction of goal function. Jorgensen (1986; 1992) has proposed to use as the goal function the thermodynamic concept energy, which is the free energy of the system compared with thermodynamic equilibrium, which may be used as "environment." The biogeochemical energy measures survival, and the idea is to test in the model which set of parameters are best fitted to give survival under the prevailing conditions.

Environmental models of today are sufficiently developed to be applied as management tools including predictions on ecological indicators, but their shortcomings are the following.

1. They are based on physicochemical principles and do not consider ecological properties of the ecosystems, particularly the ability to meet changed impacts with a hierarchy of regulations and feed-back

mechanisms. Ecosystems are soft and very flexible systems. These properties should be considered in ecological models.

2. They are not able to make shifts in species compositions, which in many cases are the most pronounced ecological reactions to changes in impacts. Therefore, it is of great importance in the application of environmental models in context with ecological indication to develop structural dynamic models.

Multidisciplinary studies are basic to the concept of integrated monitoring. Monitoring activities must therefore extend across media, in a coordinated manner. Studies of different parts of specific ecosystems, for example, typically require the application of different sampling protocols, and hence a nested network approach is fundamental. In practice, integrated monitoring stations comprise the long-term multidisciplinary linkages that join additional networks (or other research activities) generally on a larger spatial scale but with less intensive sampling addressing specific issues. In this regard, the distinguishing characteristics of integrated monitoring are as follows:

- Many components of the environment are sampled in a shared study area.
- The focus is on understanding an explaining changes that are detected and on providing the basis to predict future changes.
- Interdisciplinary analyses of results are undertaken, with modeling conducted at the ecosystem level.
- Indicators of environmental health may be developed.

The components (media) of the ecosystem of relevance are air, water (ground water, streams, rivers, and lakes), soils and sediments, flora and fauna, and humans. All of these are studied at specific locations, except for some studies of factors relevant to animals, which can introduce a need for measurements of exposure as experienced by members of the community at risk. In particular, exposure monitoring for people introduces a need for measurements distributed in space. such measurements may be tied to "bench - marks" provided by integrated monitoring sites an may eventually result in methodologies to use integrated monitoring data to assist in estimating exposure. The linkage between fixed location integrated monitoring data and personal exposure information need for applications such as human health risk assessment is currently instinct. Integrated monitoring as promoted here offers an opportunity to coordinate intensive fixed-station, multimedia sampling with monitoring programs involving human health and related personal exposure.

As was shown by B. B . Hicks and T. G. Brydges (1994) a central theme of integrated monitoring is the concept of nested networks, in which different parts of the overall problem using arrays of sites that are specially selected. This tiered approach is the only mechanism by which the problems of multidisciplinary monitoring and analysis can be addressed without requiring that all sites of every network make all of the measurements that are required to answer every question.

Nested networks are required, such that more comprehensive sites would constitute an integrated monitoring network for multidisciplinary measurement, and such that these would be operated in conjunction with less comprehensive sites distributed over a much wider space scale.

9. Integrated Environmental Data Base

Other essential problems of indicators formatting is environmental data collection and analysis. The need for reliable and up-to-date environmental information for prediction and decision making on regional, national and international levels was pointed out again at the United Nations Conference on Environment and Development, held in Rio de Janeiro in June 1992. According to Agenda 21, decision making based on adequate information requires both bridging the data gap and improving information availability. some databases such as European CORINE and UNEP-GRID, are examples of attempts to satisfy such requirements. In spite of their usefulness as methods of systematic data collection and analysis, their potential application in environmental planning and decision making is very limited. This is due to the lack of a conceptual scheme related to the functioning of natural systems. Computer technology applied to the environment (Fabos, 1988; Moffat, 1990) often runs the risk of building a large environmental data bank with the only aims of storing all sorts of data related to nature and its exploitation by man, in such a way that it can be consulted usefully *a posteriori*. The stored information probably involves an exhaustive collection of natural data (biological species, habitat types, ecological typology, micro climates, etc.), agricultural data (crops, tree plantation, grazing areas, typology of animal breeds, etc.), socio-economic data (population, employment, per capita income, standard of living, etc.), industrial data, etc. While many of these data will probably never be used in management, they nevertheless occupy the same space as others used in regular consultation. Thus, the requirement is to keep only the essential data instead of storing everything. This does, however, imply a very complex design from the information model, including the simulation and data models, to the closely-linked computer model. Information on this complex system may be organized on different levels of detail from general approaches, offering an overall version of the system, to detailed descriptions which are composed of a wide range of factors that provide minute information the system that is so detailed that it impedes a vision the whole unit.

"Environment" can now be understood as the system in which the human and natural systems interact. The former includes economic, sociological, cultural and technological elements. The later includes physico-chemical and biological elements. In addition, all these elements are complex systems and their relationships are also complex, including different spatial and temporal scales.

Full comprehension of the structure and function of the environment is particularly dependent on the availability of reliable information to enable management decision makers to use scientific rather than intuitive criteria, as is often the case. The latter causes many local decisions and large development projects actually to be experiments carried out directly on the environment, and not on trial-and-error simulation tests which would back up truly rational decisions. This information does not consist of large collections of data, or even their computer storage and retrieval. The roots of environmental mismatches are not a result of lack of data so much as a lack of significant information flows between the different component of a complex system, such as the environment. the resolution of these difficulties should be based on information systems which contemplate environmental management from a systemic and space-time dynamic perspective. The design philosophy of these systems recognizes that the environment is *per se* a very complex system with highly diverse interacting variables. This recognition emphasizes the need to include logical procedures and conceptual frameworks which reflect the dynamic character of natural systems while constituting a model for decisions to be made on their rational usage

A conceptual basis and general structure of the information system for environmental planning (SIPA) based on a set of data which closely represents the aspects of the environmental reality was elaborated recently by C. L. de Pablo and others (1991).

The essential aim of the SIPA system is to supply the elements needed to design a environmental management policy . This aim implies an analysis of "significant environmental information" according to the management needs of a previously detected set of problems. The object identification of the seriousness of each problem serves as a basis for a system of management priorities.

Environmental decision support systems (EDSS) are beginning to become available which utilize concepts from the discipline of information systems (Guariso and Werthner, 1989). The standard description of a DSS is an interactive computer system which assists decision makers to solve unstructured (or loosely structured) problems. Thus, the intention that they can be applied to a broad class of problem, each instance of which is specified through a dialogue between the EDSS and the manager.

In the *standard* DSS, there are three modules: a database management system (DBMS), a model base management system (MBMS) and a dialogue generation and management software (DGMS) module with large databases, front-ended by a *user-friendly* interface, often graphical.

The interface between the database ad the user is the database management system (DBMS) with commands input through the DGMS. The DBMS is a standard software tool in information systems providing a transparent interface. The user, in running applications software, need not be concerned with how data are stored in the database. The DBMS essentially provides the *translation* between the user's logical model of the data to the physical record and file structure of the data in the database itself.

The MBMS is fashioned on the DBMS, serving a similar purpose, and gives a DSS its special characteristic of an integrated, often synergistic, software system across these three different modules. the model base management system is thus able to cross-reference models within the model base, in the more advanced EDSS even creating new models by prototyping.

More precisely this approach discussed in the paper of B. Hendersson - Sellers and others (1993).

The emphasis is shifting in natural resource management from inventory an exploitation to an integrated, broad-scale approach with the goals of maintaining diversity, balance and long-term productivity of the environment. accomplishing this requires an understanding of spatio-temporal processes on a detailed, integrated and formalized level. The advent of satellite and other forms of observational data has made the empirical study of large-scale, complex spatio-temporal processes possible. The need to assimilate this wealth of information when making decisions is increasing the demand for integrated computer-based tools for storing, manipulating and analyzing environmental data. Perhaps the most versatile of the tools now available is the geographic information system (GIS).

A *geographic information system* is an integrated software package specifically designed for use with geographic data that performs a comprehensive range of data handling tasks. These tasks include data input, storage, retrieval and output, in addition to a wide variety of descriptive and analytical processes.

In summary, technology is to provide ways to visualize, compare and analyze spatial relationships among large amounts of diverse data. Just a maps have made it possible to view that comprehend the physical , social and political distribution on the earth, GIS provides a much more powerful window on attributes of today's environments. GIS now represents a powerful and flexible tool for managing resources and understanding and predicting complex and changing systems-from climate to habitats.

Investigation of environmental change requires analysis of processes involved on a detailed level, integrated models that can predict environmental response over a wide range of space and time scales, as well as the capacity to translate those predictions into an environmental indicators format from which people can make decisions.

The last few years have seen an upsurge of interest in a new approach to software engineering: object technology (OT). It has been shown to be extremely useful in modeling business environments and, as a consequence of its origins in simulation modeling components of the water industry.

The essence of object technology is a focus of the *objects* that constitute the problem and their interrelationships, and lesser concern with the flow of control within a model. This is claimed not only to bring the modeler closer to a realistic description of the problem but also to provide reusable designs, frameworks and coded modules. In addition, it provides a greater capability for scaling up to larger systems that previously possible (Booch, 1991) - in a way that is understandable to mangers and technicians alike (the so-called *seamless paradigm).*

Object-orientations based upon essentially three concepts: encapsulation and information hiding; abstraction by classification; and polymorphism as implemented through inheritance (cf. Hendrson-Sellers, 1992). Encapsulation and information hiding are not especially new, but the degree to which they are used by object technology is new. State and behavior are encapsulated together into a *class.* Much of this information is hidden inside the class. Only those characteristics which offer *services* to objects of other classes are visible outside the class. Consequently each class is as self-contained as possible. Classification is a type of abstraction process used to represent the complexity of the real world by grouping ideas into classes of things.

Part 11:

Development of Environmental Indicators on the Basis of Response Functions Method

10. The Method of Response Functions

As it should be clear from the review given above, for the last few decades the problem of environmental indicators and indices is in the special focus of attention of scientists as well as decision makers.

However the problem in general is so complicated, that until now there is no unified theoretical basis for the formation of scientifically substantiated system of indicators. At the same time, the operational process of environmental quality index is generally simple (Couillard and Lefebvre, 1985). Most indices use parameters, weightings, rating curves and aggregation methods. We will analyze briefly each operation for a better understanding of this procedure.

The *weighting* aims to assign a relative importance that differs for every parameter. The relative importance is usually expressed through a coefficient, called weighting factor, and interrelates the importance of one given parameter with that of the various parameters used in the index. The sum of all weighting factors is generally 1.0. This way, the most important parameters are given the higher relative weight, and conversely.

The widely used *rating curve* links a parameters concentration with the quality of the environment. This is feasible using a graph or a mathematical function that transforms each value of a parameter to an approximate value or "score". Each parameter is represented by a quality curve that is based on criteria inherent to the parameter. Quality scores are proportional to the improvement or to the deterioration of the quality of the environment, and their values range from zero to some power of 10 (i.e. 0-1, 0-10, 0-100). Moreover, the lower and the higher limits are the same for each rating curve of an index. The main advantage of a rating curve is that it rapidly transforms the concentration of a parameter into a quality score, thus representing the quality of environment for a given use. It also makes it possible to go from a parametric to a non-dimensional system, i.e.,. to eliminate concentration units (which often differ from one parameter to the other), thus simplifying calculation of the overall index.

The *aggregation process* is used to consolidate all quality scores of rating curves and, if necessary to weight these scores in terms of a given weight. It is after this step that the final result (environmental quality index) can be obtained. The literature contains many methods for calculating the aggregation function. Table 2 lists the principal methods used and their corresponding mathematical expression.

The literature also contains modified versions of the above formulations, as well as other specific aggregation methods. House and Ellis (1980) report a technique derived from the additive form - the Solway River Planning Board's version of the weighted sum (Table 2, equation 8) or of the unweighted sum (Table 2, equation 7). Some aggregation methods are based on more complex statistical considerations, while others use a combination of the additive form and simple parameters. Finally, some indices are made of a single parameter or elaborate formulae whose result is relative, i.e. comparable for the same context of application (Frechette and Cluis, 1983).

Further we will examine the new theoretical approach to the formation of ecological indicators, based on the method of response functions.

As we have already mentioned, the formation of ecological indicators is determined significantly by the ability to forecast the response of ecosystems resulted from the changes of external impacts.

The concept of "response functions" of environmental problems was derived in connection with the quantitative evaluation(Fritts et al., 1971; Larher 1976; Odum 1971; Whittaker 1975) of the effect of environmental factors on various life indices of organisms and biological systems; for example, the intensities of growth and development, productivity, life span, mortality, metabolism, etc. Each of these indices is influenced by a set of environmental factors, of which the values in the moment τ are considered to be components of the vector $X(\tau) = [X_1(\tau),..,X_n(\tau)]$, where n is the number of the factors taken into account.

The main features of the process of the environmental indices' formation is clear from Fig. 11. It is evident that we especially pointed-out on stress-response relationships.

In order to have effective ecological policy designs, one must have a clear understanding of the resilience and stability properties of ecological systems and of the institutional and societal systems with which they are linked. Any pervasive understanding requires that the underlying scientific paradigms be well understood. Stress is a concept that appears to be one aspect of ecological science that underlies a more complete understanding of the impacts of antropogenic perturbations, the assessment of which is necessary for the development of policies for environmental or ecosystem management.

There have been numerous definitions and concepts of stress offered by research workers during the past several decades. Stress has been viewed as a response to external or internal processes which reach those threshold levels that strain psychological and physiological integrative capacities situated close to, or beyond, their limits. Stress has also been defined as any force that purchase the functioning of a critical subsystem beyond its ability to restore homeostasis. Regardless of how stress is defined and regardless of the stressor involved, the concept, as usually employed, involves an interference with the normal function of a system; its effects are most dramatically observed after certain thresholds of tolerance are exceeded, and it appears that, beyond these thresholds, any recovery is problematical or at least difficult.

So, returning to our main problem, let us designate as $\varphi_k[X(\tau)]$ the response function of the characteristic k to the impact of the factors $[X_1(\tau),..,X_n(\tau)]$.

Now as it is well known, the main problem is the actual choice of the function$\varphi_k[X(\tau)]$. Even if there are a large number of influencing environmental factors, usually it is possible to single out the number m of the environmental factors which make the main impact on the index that is taken into account. The impact of the other factors can be regarded as "ecological noise", superimposed on imperative factors.

It is clear that in many cases one cannot evaluate experimentally the view of the generalized response function $\varphi_k[X(\tau)]$. Thus the problem is usually divided into a set of subproblems, taking into account the definition of the partial response functions f_i to every environmental factor x_i. In typical cases, the graph of the partial response function f_i to the variability-of the factor x_i is a unimodal or S-shape curve.

The interval $x_i = (x_i^{\min}, x_i^{\max})$, limited with the maximal and minimal values of the factor x_i, is called the tolerant interval on the given factor, and the point (or the interval) x_i^{opt} in which the index reaches the maximal value is called the optimal point (interval or zone) on the given factor. For the indices that have the maximal value in unfavorable conditions, the concepts of the tolerant interval and optimal point are changed correspondingly.

Following the designation of the equations in parametric form, there is the problem of the definition of the generalized response function $\varphi_k[X(\tau)]$. The most important question here is in what way the tolerant interval, the position of the optimal point on it, and also the view and the scale of the partial response function of the given factor depend on the values of the other factors and their variability. Until now these questions have not been resolved either theoretically or experimentally.

Furthermore, there is the problem of the formal representation of the mutual influence of the factors (aggregation problem) on the index and, respectively, of the presentation of the partial response functions in the generalized form. Usually the additive and multiplicative forms are used. The potentialities of the multiplicative representation of the environmental factors' impact on the biological processes have been discussed repeatedly. Basically, it has been criticized that the multiplicative form represents the independence of the influencing environmental studies (Mitscherlich 1954; Heath 1969), the potential of the multiplicative form is broad enough, and its use can give some interesting results. In the following section this approach is discussed in more detail.

After the selection of the response functions' view $\varphi_k[X(\tau)]$ we solve the problem of the combine evaluation of all parameters taken together. This approach allows us to consider the mutual influence of the factors on the dynamics of ecosystems.

This approach free from the most frequent criticisms of indicators related to aggregation rules, which in common case are either additive, multiplicative, or maximum or minimum operators (Ott, 1978).

We will base on the definition of ecosystem health which is linked to the diversity and/or complexity of the system. The idea is that diversity and/or complexity are predictors of stability or resilience and that these latter are measures of health. This linkage has been a subject of much controversy in the ecological literature and sentiments have changed several times. Because diversity is so easy to measure in ecosystems it has come to be a prime *de facto* indicator of health. According to S. L. Pimm (1984) there are several interesting aspects of the problem that have yet to be investigated, (see Fig. 10). Recent advances in network analysis (Wulff et al., 1989) hold some promise in allowing a more sophisticated view of the organization of systems, not just their numbers of parts as reflected in diversity.

One of the most important variable in Fig. 10 is stability, presumably discussed in the monographs (Pykh et al., 1980; Pykh 1983) is defined through various functional characteristics, each of which could be used while describing various aspects of human impacts on environmental health/quality.

Stability and the related concept of resilience have much to recommend them as general measures of health. Healthy organisms are those that have the ability to withstand disease organisms. They are resilient and recover quickly after a perturbation. This then leads to a definition of health as the ability to recover from stress. The greater this ability the healthier the system. A problem with this definition is that it says nothing about the operating level or degree of organization of the system. A dead system is more stable than a live system because it is more resistant to change; but it is certainly not healthier, nor is it resilient. an adequate definition of health should also incorporate a statement about the level of activity and organization of the system.

We'll examine the ecological indicators of environmental health/quality in the framework of responses functions method. We'll demonstrate the examples of our various definitions of how various definitions of stability of stability could be fruitfully used while examining the impacts of various types of human activity on the state of environment.

11. Example 1. Environmental Indicators of Radioactivity Releases

The movement of radionuclides in the environment is regulated by the complex relationship of many physical, chemical, an biological factors. When introduced into air or water, radionuclides disperse, but can ultimately accumulate in specific components of the environment. A highly simplified illustration of the movement or radionuclides in the environment, from source to receptor, is illustrated in Fig. 12 (Bascicetto and Higley, 1992).

Recognition and understanding of the seral stage of the site can help in predicting the long-term movement of the radionuclides under consideration because the fate and potential effects are determined not only by the amount and type of radionuclide, but by community characteristics as well.

Ecosystems vary considerably in how they cycle radionuclides, depending on the seral stage of the component communities (Whicker and Shultz, 1982).

Studies have shown that the mobility of radionuclides in soils and sediments is dependent on a host of physicochemical and biological factors that govern the geochemical mobility and availability of the radionuclides to plants. Numerous factors, including season of the year, moisture, sunlight, chemicals, competition, and parasitism, affect the response of a biological system to radiation exposure.

Ecosystem functional processes, including the cycles that move nutrients (or radionuclides) through the biosphere, can be monitored; they can also be affected by the presence of radionuclides. Radionuclides frequently behave as nutrient analogous, with one important difference: the radionuclide concentrations are generally so small, even at levels that could cause biological damage, that generally (unlike their nutrient analogies) they are not biologically regulated. As a result, radionuclides generally behave as tracers in ecosystems.

Assessment of the potential ecological impacts of radionuclides requires the radio-ecologist to track or predict their movement through various environmental media. Also required is an understanding of the radiation or chemical toxicity of these materials to the biota at the observed or predicted environmental concentrations.

The main requirement is a system of models quantitatively describing radionuclide behavior during the time period between environmental input and man's intake of and/or external exposure to the radioactivity.

The conceptual model is a useful tool for understanding the nature and extent of contamination. It will help investigators identify the site-specific potential exposure pathways to humans and environmental receptors such as biological species or the environmental media necessary for their survival. In addition to the known or potential receptors such as biological species or the environmental media necessary for their survival. In addition to the known or potential receptors, the site conceptual model should include known and suspected sources of contamination, types of contaminants and affected media, known and potential routes of migration (Bascicetto and Higley, 1992).

The model of radionuclides dynamics in the elementary ecosystems, including the lower atmosphere, soil, vegetation, surface water and hydrobionts has been elaborated, using ^{90}Sr as an example (Malkina and Pykh 1988; Pykh and Malkina 1991; Pykh and Malkina - Pykh 1992).

The lower atmosphere, soil vegetation, and surface and underground water are closely connected with various migratory flows of matter and energy in and out of single geosystems. The functional unity of the geosystem on any hierarchical level, i.e. the interaction of all its components, can be recognized only within an area of suitable size. The concept of an elementary unit of landscape is derived from the fact that the geosystem cannot be divided infinitely.

An elementary landscape-geochemical system is a three-dimensional system, within which the composition and migration patterns of chemical substances of the landscape's components are similar enough to enable a unity of system, within which the composition and migration patterns of chemical substances of the landscape's components are similar enough to enable a unity of system structure and function to be recognized. Within the boundaries of the elementary landscape, interaction between individual units is more significant than the external interactions of this elementary landscape with other landscape-geochemical systems.

The pollutants, entering any unit of the elementary ecosystem (EE) involved in the following processes: (1) accumulation in one unit: (2) decomposition in the unit (for the organic pollutants): and (3) transfer to the other units of the EE. Thus, the process of self-purification of a certain component of the EE results in the pollution of the other components. The process continues until the pollutants are completely decomposed (mineralized) or until they are removed beyond the confines of a given EE. To examine the successive transference and transformation of the pollutants through the units of the EE: lower atmosphere, soil, vegetation, surface water. Here, one must note the specific features and some restrictions, assumed in this version of the model: (i) the flow of pollutant from one EE to another was not examined, (ii) the model is elaborated now for the radioactive pollutant ^{90}Sr because of its great scientific interest - long half-life (28 years), excessive mobility in ecological chains, and ability to concentrate in the bones and muscles of living organisms. Also, it is obvious that the simulation of the pollutant flow dynamics as the process of accumulation, or self-purification in some cases, depends on the choice of the simulator.

The general equation of the decrease of the amount of the pollutant, making its appearance in any unit of the EE over-time, is obvious and was used repeatedly

$$P(t) = P(t_0)\exp(-\varphi_n \cdot t), \qquad (11.1)$$

where $P(t)$ is the pollutant concentration in the EE unit is the initial concentration of the pollutant at a given time $t, P(t_0)$is the initial concentration of the pollutant at a given time t_0, φ_n is the parameter of the decreasing rate of the pollutant. the last mentioned depends on the factors taken into account for example physico-chemical properties of the environment or of the pollutants and so on.

We consider φ_n as some generalized response function of the resistance index of the EE unit on the specific values of the environmental characteristics that determine this resistance. We define the resistance index as the index of the EE units ability to resist the pollution flow either due to the self-purification ability or due to the decrease of the accumulation rate. The generalized response function is determined as:

$$\varphi_n = \prod_{j=1}^{n} f_j(x_j, \alpha_j), \qquad (11.2)$$

where f_j are the partial response functions of the resistance index to the factors x_j and α_j is the parameters' vector. The additional restriction is:

$$\max_{x_j} f_j(\alpha_j, x_j^{opt}) = 1.0. \qquad (11.3)$$

Then, the amount of pollutants accumulated in the EE unit, is described usually with accumulative coefficients, that is the ratio of the amount of pollutants in the unit to the amount in the environment and expressed in the following form:

$$P(t)=P(t_0)\cdot(P_{\max}(1-\exp(-t/\varphi_n))), \qquad (11.4)$$

where $P(t_0)$ is the initial concentration of the pollutant in the environment (in the soil for the vegetation, in the water for hydrobionts) in the moment $t_0, P_{\max}$ is the upper limit of the concentration of pollutant in the unit and φ_n in this case is the generalized response function of the resistance index, determined using Eq. (11.2) with the corresponding f_j.

Now, let us determine the concrete sense of the functions f_j for every EE unit and give the corresponding descriptions of the model of EE self-purification ability. It should be pointed out here that the process of decomposition is not essential for radionuclides and therefore is not taken into account in the present version of the model.

Atmosphere. We didn't elaborate our own block of atmosphere contamination because a lot of highly professional scientists are dealing with these problems. Any of the existing model of pollutant's dynamics in the atmosphere could be used as a block in our model (for example RAINS is under consideration).

In the present state of the model we use the most simple dependencies of the pollutants' deposition on the underlying surface and the amount of pollutants in the atmosphere and the state of the atmosphere as well

The appearance of radionuclides on the soil surface takes place mainly in two ways: deposition from the atmosphere (dry deposition and washing), and also by rain-wash of deposited pollutants from the plant cover. According to Teverovsky (1985) in the case of transitory deposition, the amount of pollutant $A_s(\mathrm{Ci}/\mathrm{m}^2)$, appearing on the soil surface, is determined with the equation:

$$A_s = Q_0 \cdot (G \cdot V_g + \Lambda \cdot G^z) \qquad (11.5)$$

and in the sufficient distance from the source of deposition with the equation:

$$A_s = Q_0 \cdot G(v_g + \Lambda \cdot H_z^{\max}), \qquad (11.6)$$

where $Q_0(Ci)$ is single deposition, v_g is the spread of dry deposition of the pollutant (m/s), G is the meteorological dilution factor (s/m^3), Λ is the constant of the pollutant's washing away with precipitation $(s^{-1}), G^z$ is the integral by the vertical axis Z of the dilution factor $G(s/m^2), H_z^{\max}$ is the maximum height of the pollutant mixing level in the atmosphere (m).

Soil. To elaborate the soil block we take into account characteristics of the behavior of radionuclides in different soil types.

The radionuclides on the soil surface appear as result of predominantly atmospheric deposition - dry deposition and washing off - taking into account the initial delay with the underlying plant cover. The coefficient of initial delay of grassland is equal nearly 25% of the total radionuclides' deposition, for forests this value varies between 40% and 90 % in some special cases (Aleksachin 1982). The special attention in our model is devoted to the agricultural crops, the values of the coefficient of initial delay of the other vegetation types are important when calculating the coefficient of the surface run-off.

One of the most important factors influencing the amount of the absorbed pollutants is the content of cations. According to research, the concentration of absorbed pollutants increases with increasing cation content and also with the increase of the absorption capacity. The discrepancy between the value of the absorption capacity and the amount of absorbed pollutants can be explained by the difference in the mineral composition of the inorganic part of the soil, especially with its highly dispersed gley components. The accumulation rate is affected by the humus content and its composition. Also, the accumulation rate is influenced by soil pH. For pollutants such as radionuclide, the absorption capacity increases with increased pH value.

The rate of washing away of pollutants from the soil surface depends on the amount of radionuclides in soil, the strength of its fixation in soil profile and the layer of surface runoff. If the pollutant flow is constant, then the rate of the washing away depends linear on the annual layer. In a single case of contamination usually there is no such dependence.

Thus the soil block in the model of pollutant dynamics in the elementary ecosystem will be described in the following form:

$$
\begin{aligned}
&P_s(t_0) = A_s(1.0 - K_i^c) \\
&P_s(t) = P_s(t_0) \cdot \exp(-F^s \cdot g^s \cdot t) \\
&\varphi_s = f_1^s(pH) \cdot f_2^s(HU) \cdot f_3^s(E) \cdot f_4^s(Ca) \cdot f_5^s(GL) \\
&f_1^s(pH) = \alpha_1^s \cdot pH^{b_1^s} \cdot \exp(-c_1^s(pH/(pH_{\max} - pH))^{\gamma_1^s}) \\
&f_j^s(x_j) = 1 - \alpha_j^s(1 - \exp(-b_j^s \cdot x_j))^{c_j^s} \qquad j = 2,..,5 \\
&P_s(t) = P_s(t)/\lambda \cdot (1.0 - K_m^s)
\end{aligned}
\tag{11.7}
$$

where $P_s(t_0)$ is the pollutant concentration in the t_0 moment in soil (Ci/km^2), K_i^c is the coefficient of the initial delay of radionuclides by plant cover $(day^{-1}), i$ is the index of plant cover (grassland, forest, agricultural crop stand), $P_s(t)$ is the pollutant concentration in the soil in the t moment

(Ci/km^2), pH is soil acidity, HU is the humus content (%), E is the absorption capacity (mg equiv./100g) , Ca is the calcium cation content (mg equiv./100 g), GL is the clay content (%), F^s is the generalized response function of the resistance index of soil, f_j^s are the partial response functions of the resistance indices of the soil, K_m^s is the coefficient of the surface run-off of the radionuclide (day^{-1}), m is the index of the geographical zone, λ is the constant of radioactive decay (day^{-1}) and $pH_{\max}, \alpha_j^s, b_j^s, c_j^s, d_j^s, \gamma_j^s, g^s$ are parameters, $j = 1,..,5$.

We consider F^s as some kind of the generalized response function of the resistance index of the given unit of the ecosystem (soil in this case). The generalized response function of the resistance index in its turn is composed of the partial response functions depended on the concrete values of the environmental factors that determine the given resistance. In this case the well-known Weibull function used frequently as dose-response model, appears as the partial case of the proposed response functions $f_j^s(x_j)$.

Vegetation. Pollutants enter the vegetation in two main ways: firstly, the direct contamination of the plant cover with the pollutants, which come down from the atmosphere (aerial). Vegetation is the initial screen holding up the fall-out of the pollutants from the atmosphere. In this way pollutants may be absorbed by the plant tissues. Secondly, pollutants from the soil enter the plants through the roots via the soil.

Direct contamination is caused only by the deposition of pollutants from the atmosphere on the plant cover during the vegetative period. The contamination of the plants through the roots depends on the amount of pollutants in the soil and the physico-chemical properties of the soil. The initial amount of pollutants caught by the vegetation aerial is determined by the moment of contamination which in its turn determines such plant cover's characteristics as the leaf area index (ratio of the total area of the leaves to the corresponding soil surface (m^2 / m^2), depending on biological characteristics and the development phase of the species. It might well be assumed that the amount of pollutants caught corresponds with the leaf area index in the same way as the incident radiation corresponds to the catching rate, decreasing exponentially as the leaf area index increases.

The migration of pollutants in the soil-vegetation link is determined by the physico-chemical properties of the soil, affecting the accumulation and fixation of the pollutants. It was shown above that the soil properties are the main factors determining the pollutants status in the soil and the intensity of their accumulation by plant roots, soil pH, absorption capacity, humus content and cation content influence significantly the strength of fixation of the pollutants in soil and, hence, their accumulation in plants.

The accumulation rate in the soil-vegetation link is affected seriously by the absorption capacity and, in particular, by the amount of cations. In soils with a low concentration of Ca^{++}cation the accumulation of pollutants such as ^{90}Sr by plants is more intensive than in soils with a high concentration of these cations. Soil pH also plays an important role in the pollutant accumulation by plants. Thus, in general, it might well be assumed that the strong fixation of the pollutants in soils prevents their accumulation by plants. Also, the accumulation rate depends on the biological characteristics of the species, in particular on the existing barrier mechanisms towards certain pollutants.

The vegetation block of model is described as follows:

$$\begin{aligned}
&P_a^v\ (t\ ) = A_s \cdot K_a^{g,s}{}_c \\
&K_a^g\ = t^{'b_1^c} \exp(-c_1^c \frac{t^{'\gamma_1^c}}{t'_{\max} - t}) \\
&K_a^s = \alpha_1^c \exp(-d_1^c \cdot t') \\
&P_s^v\ (t) = P^s\ (t) \cdot (K^v\ (1.0 - \exp(-g^v\ \cdot t / F^v))) \\
&F^v = f_1^v(pH) \cdot f_2^v(E) \cdot f_3^v(HU) \cdot f_4^v(Ca) \cdot f_5^v(R) \qquad (11.8) \\
&f_j^v(x_j) = \gamma_j^v(1.0 / (\alpha_j^v + \exp(b_j^v - c_j^v \cdot x_j)) - d_j^v) \qquad j = 1,\ldots,6 \\
&f_5^v(R) = 1.0 - \alpha_5^v(1.0 - \exp(-b_5^v \cdot R))^{c_5^v} \\
&P^v(t) = P_s^v(t) + P_a^v(t),
\end{aligned}$$

Where K_a^g and K_a^s are the aerial proportional coefficients for the grain and stem correspondingly, $P_a^v(t)$ and $P_s^v(t)$ are the concentrations of pollutant in the biomass (grain or stem) resulted from aerial or soil contamination correspondingly (nCi / kg), t' is the moment of aerial contamination (days from the sowing), K_v is the upper limit of the pollutant concentration in plants (nCi / kg), R is the amount of precipitation (mm / day), F^v is the generalized response function of the vegetation resistance index, f_j^v are the partial response functions of the resistance index, $P^v(t)$ is the total concentration of the pollutant in vegetation (nCi / kg), $\alpha_j^c, b_j^c, c_j^c, d_j^{c,v}, \gamma_j^{c,v}, g^v, t'_{\max}$ are parameters.

Surface water. The main sources of pollutants in the surface water are deposition from the atmosphere and washing away from the soil surface. The level of contamination by pollutants in the surface water is affected by purification processes and streamflow dilution and then by accumulation by hydrobionts and floor deposits.

The accumulation of the pollutants by the hydrobionts (freshwater plants and animals), is determined by the water pH, temperature and illumination. It was shown that the level of ^{90}Sr accumulation by hydrobionts is inversely proportional to the concentration calcium ions in water. This phenomenon takes place because of the fact that Ca and ^{90}Sr are chemical analogous and have the same physico-chemical properties.

One must take into consideration the fact that pH values significantly affect the metabolism of hydrobionts. The specific interval of the pH value is considered to be optimal for the life activity of every organism; beyond the confines of this interval the suppression and destruction of hydrobionts take place. The variability of accumulation rate depends significantly on the pH values. The increase of temperature in the given interval for the tolerant species stimulates the growth and metabolism of hydrobionts: hence, the stabilization of the equilibrium accumulation level takes place more intensely than at lower temperatures. The accumulation rate of pollutants by the water plants is closely connected with light conditions. The accumulation of a wide set of pollutants is more intensive in natural illumination that in dark conditions.

Also the model is describing the accumulation of radionuclides by different types of floor deposits. The absorption capacity of floor deposits depends on the size of gley particles, physico-chemical properties of radionuclides and the composition of solid phase. We used the equation from (Kozlov 1991) and verified its parameters for various types of floor deposits.

All other condition being equal the accumulation level of silt is definitely higher then of sand. This fact in its turn influences the level of hydrobionts' accumulation. The total amount of radionuclide accumulated by hydrobionts in the lakes with predominantly sand as floor deposits is rather low then in that with the silt.

We describe one pollutant's dynamics in the surface water as follows:

$$\begin{aligned}
&P^{w}(t) = A_{s} + P^{s}(t)\cdot K_{m}^{s}\\
&P^{h}(t) = P^{w}(t)/\lambda\cdot(K^{h}(1.0-\exp(-g^{h}\cdot t/F^{h})))\\
&P^{sed}(t) = P^{w}(t)/\lambda\cdot K^{sed}\cdot S^{sed}(1.0-\exp(-\lambda\cdot t))\\
&F^{h} = f_{1}^{h}(pH)\cdot f_{2}^{h}(L)\cdot f_{3}^{h}(T)\cdot f_{4}^{h}(Ca)\\
&f_{j}^{h}(x_{j}) = 1.0-\alpha_{j}^{h}(1.0-\exp(-b_{j}^{h}\cdot x_{j}))^{c_{j}^{h}} \quad j=1,..,3,\\
&f_{4}^{h}(Ca) = \gamma_{4}^{h}(1.0/(\alpha_{4}^{h}+\exp(b_{4}^{h}-c_{4}^{h}\cdot Ca))-d_{4}^{h})\\
&P^{w}(t) = P^{w}(t)-P^{sed}(t)-P^{h}(t)/\lambda,
\end{aligned} \tag{11.9}$$

where $P^{w}(t)$ is the ${}^{90}Sr$ concentration in the surface water in the moment $t\ (nCi/litre), P^{h}(t)$ is the concentration of the pollutant in hydrobionts $(nCi/kg), K^{h}$ is the upper limit of ${}^{90}Sr$ concentration in hydribionts $(nCi/kg), P^{sed}(t)(nCi/kg), P^{sed}(t)$ is the ${}^{90}Sr$ concentration in sediments $(nCi/kg), K^{sed}$ is the transfer coefficient of ${}^{90}Sr$ into the sediments $(litre/(kg\cdot year), S^{sed}$ is the surface density of sediments depended on the sediments type $(kg/m^{2}), L$ is the illumination $(lx), Ca$ is the calcium ions concentration in water $(g/litre), T$ is the water temperature $({}^{0}C), F^{h}$ is the generalized response function of the resistance index of hyrobionts, f_{j}^{h} are the partial response functions of the resistance index of hydrobionts, λ is the constant of radioactive decay $(year^{-1}), \gamma_{j}^{h}, \alpha_{j}^{h}, b_{j}^{h}, c_{j}^{h}, d_{j}^{h}, g^{h}$ are parameters.

Also, if the source of the radionuclides is permanent (such as nuclear plant exploitation, etc.,), then the equation for radionuclide concentration C_n in any unit of the elementary ecosystem after the n years is equal

$$C_n(t) = \frac{C(t_0) \cdot K_c(1.0 - K_c^n)}{1.0 - K_c} \qquad (11.10)$$

where K_c is the coefficient of pollutant's concentration decreasing resulted from the submodels (11.7), (11.8), (11.9) respectively.

The parameters of the model were evaluated in a wide set of data from the literature as well as from field experiments. It should be notify that ***the parameters' evaluation in each case is provided for the generalized response functions*** F^s, F^v, F^h ***but not for their partial components*** f_j^s, f_j^v, f_j^h**.** For example, the non-linear least square problem for the parameters' estimation of the soil generalized response function F^s is described as follows:

$$\sum_{t_1}^{t_5} \sum_{k=1}^{5} (P_s(t_0)\exp(-F^s \cdot g^s \cdot t) - P_s^k(t))^2 \Rightarrow \min, \qquad (11.11)$$

where $P_k^s(t)$ are the experimental data on ${}^{90}Sr$ concentrations in soil layer 0-30 cm for the 2, 4, 6, 8 and 10 years after the initial contamination; $P_s(t_0)\exp(-F^s \cdot g^s \cdot t)$ is determined from the submodel (11.7). The respective parameters' estimating was done for the submodels (11.8) and (11.9).

In Fig. 13 the partial response functions of vegetation resistance index (for spring wheat) to such characteristics as soil pH, absorption capacity, Ca ions and humus content are presented. The maximum error of evaluations is not more than 10%. The testing of the model was done on the independent data for various soil types and lakes in various climatic conditions and geographical zones. Some of the test results are shown in Fig.14. We can say that the predictive abilities of the model are high.

Partial response functions, received after the parameters evaluation could be also used for calculation of resilience index of each unit of the ecosystem under study. Let us give an example. We calculated the values of general response functions of vegetation F_v for various soil types, i.e. we elucidate which soil type is the most favorable for the decreasing of pollutants flow into the crops. For the soil types under study the values of F_v are as follows: podzolic soil -0,04; sod-podzolic - 0,23; gray forest - 0,58; ordinary chernozem - 0,90. Thus it is clear, that the worst situation for the accumulation of ^{90}Sr by plants takes place in podzolic soils, and the best is in chernozems. Further if it is necessary to examine which soil property is the most valuable in this resilience index, we can do it, looking through the values of concrete partial response functions f_j. This kind of analysis can be provided for each unit of the ecosystem.

A set of computer experiments was provided on the model of radionuclides dynamics, the results of these experiments are demonstrated on Fig. 15-18 and give a good presentation of ^{90}Sr behavior in the units of ecosystems in various geographical zones.

It was simulated the single deposition (air contamination) of ^{90}Sr in amount of 80 000 *Ci*, and ^{90}Sr dynamics during 10 years after the moment of contamination was examined. Also the cases of initial contamination taking place in winter and in summer time were calculated separately. In summer time the scenario of ${}^{90}Sr$ deposition on the agroecosystem of spring wheat was examined.

Fig. 15 demonstrate the ${}^{90}Sr$ dynamics in case of deposition in winter and summer time in the soils of various ecosystems. We accept that for the elementary ecosystem the atmospheric source of contamination in case of single deposition plays an important role only in the first year after deposition (accident). And after this the cloud of contaminant leaves the boundaries of elementary ecosystem.

The most favorable from the soils' self-purification point of view is the EE of middle taiga. In the chernozems soils of steppe zone after a 10 years period nearly 90% of entered contaminant is appeared. Subtropical soils occupy the intermediate position. The explanation can be given to a certain extent of soil contamination on the second year after the initial moment, because some amount of ${}^{90}Sr$, caught by the crop stand, appears in soil.

It is natural that if we are examining the ${}^{90}Sr$ accumulation in plant, this situation is inverse. (Fig. 16). The seeds of spring wheat accumulate the greatest amount of radionuclide while cultivated on sod-podzolic soils in case of summer contamination (flowering stage). The rapid decreasing of ${}^{90}Sr$ in the seeds of spring wheat in the second year after contamination could be explained by the great role of air source of contamination during the moment of deposition. Resulted from the winter contamination radionuclide's concentration in the wheat seed on sod-podzolic soils is also very high. The most favorable from these points of views are leached chernozems. The soil source of crops contamination has nearly the constant value during 10 -years period, but its absolute value is rather low in comparison with the other ecosystems.

The distinct regularity can be observed in the dynamics of hydrobionts accumulation of ^{90}Sr in the lakes of various geographical zones . Fig. 17 demonstrates the radionuclides dynamics in *Elodea* in the lakes of middle taiga and forest steppe zones in case of sand and silt floor deposits. It is evident that the accumulation level in middle taiga is much higher because the radionuclide's run-off from soil surface is much higher then that appears in forest steppe.

Fig. 18 demonstrates the radionuclides accumulation by various types of floor deposits in the lakes of various ecosystems. The process demonstrates the same regularities as for soil and hydrobionts accumulation dynamics.

The output of the model is the radionuclides concentration's level in the main units of elementary ecosystem. After these when examining the problem of *ecological modifications* (radioecological shift) one has to transfer to the dose rates of radionuclides (*Gr* or *rad* per year), which are usually used to evaluate the consequences of radioactivity release. Some more or less complicated transfer equations exist (Romanov 1993).

For ionizing radiation effects to be observed at the population, community or ecosystem level, the doses need to be quite high. Furthermore, although low doses may cause effects at the individual level, the response may be insufficient to be observed. Natural environments can offer stress that can significantly enhance or mask the response of plants and animals to ionizing radiation. In addition, the response to environmental stress is frequently affected by interspecies relationships such that the effects of stress may often be indirect, and therefore often unpredictable.

Thus, on the base of the described model we propose the general index of ecosystem's ecological modifications resulted from the radioactive release which consists of the partial indices reflected the possible ecological modifications in each unit of the ecosystem under study.

Primarily, radioecological studies investigate the soil only as the source of radioactivity for plants and organisms. Then we use the generalized response function F^s of soil resistance index as the partial index reflecting the general ecosystem status in the situation of radioactive release.

Another partial index is determined the vegetation status. For the natural vegetation (grassland, forest, etc.,) the index reflecting the possible ecological modifications (radioecological shift) is the primary productivity P $(kg/m^2 \cdot year)$ (Spirin et al., 1988); for the agricultural crop stands - yield production (Aleksachin 1982).

We can examine the water ecosystem as a part of elementary ecosystem. In this case we can select any single index reflecting the possible ecological modification in simplest way. But we can examine the water ecosystem as the original one. Then to provide the general index of ecological modification for water ecosystem based on the partial indices for each unit of water ecosystem (water, hydrobionts, floor deposits), and to include this general index into the general index of the elementary ecosystem under study.

It is evident that the proposed index of ecological modifications can reflect the changes of the ecosystem's radioresistance resulted from the changes of the properties which determine the given resistance (i.e. soil and water pH, humus content, etc.,).

Release of radioactive material to the environment may result in significant radiation exposure of man. Radiation exposure may occur through any one of a number of exposure modes; each mode, in turn, may have any number of subordinate exposure pathways of potential importance. The exposure modes of principal importance following an environmental release of radioactivity may be classified in two groups: (1) internal (radiation source within the body, i.e., inhalation and ingestion) and (2) external (radiation source outside the body, i.e., immersion in contaminated air, submersion in contaminated water, and exposure to contaminated surface). Adequate assessment of an environmental release of radioactivity requires that consideration be given to possible dose contributions for each of these exposure modes.

Also after calculations of radionuclides concentrations in the units of ecosystem, these data can be included into the CUEX (Cumulative Exposure Index). In the latest case the transition coefficients for doses units must be used.

The Cumulative Exposure Index (CUEX) concept (Rohwer and Struixniss 1972) is being developed to facilitate realistic assessment of the radiation dose to man as a result of environmental releases of radioactivity. CUEX is defined as a numerical guide indicating the relative significance (dose estimate ÷ dose limit) of measured environmental radioactivity on the basis of the estimated *total dose* to man for *all radionuclides* and *exposure modes* of importance.

The aim in developing this concept is to assess the releases on the basis of time-integrated radionuclide concentrations measured in suitable environmental sampling media; typical measurements would be concentrations in air or water or on the land surface. The measured concentrations are assessed in relation to basic radiation safety standards recommended by recognized authorities for application to members of the public

The Cumulative Exposure Index for a given environmental release of radionuclides in calculated in the following manner:

$$CUEX_j = \sum_{i=1}^{n} \frac{E_{ik}}{DLEK_{ijk}}, \qquad (11.12)$$

where

$CUEX_j$ - a numerical guide indicating the relative significance (dose estimate ÷dose limit) of measured environmental radioactivity on the basis of the estimated total dose in the jth organ for all radionuclides and all exposure modes,

E_{ik} - time-integrated concentration $(\mu\text{Ci}-\text{hr}/\text{cm}^3-\text{yr})$ for the ith radionuclide in the kth environmental sampling medium, and

$DLEC_{ijk}$ - that time-integrated concentration ith radionuclide $(\mu\text{Ci}-\text{hr}/\text{cm}^3-\text{yr})$ the which, if present in the kth environmental sampling medium under conditions considered, is estimated to yield a dose for the jth organ, via all exposure modes, equal to the annual dose limit for the organ.

12. Example 2. Indicators of the Ecological Status of Agroecosystems and Pesticides' Dynamics

Nonpoint source loading of agricultural chemicals and sediments from agroecosystems is a measure of the efficiency of the agroecosystem with respect to resources an inputs, and a measure of the potential for contamination of surrounding areas. Nonpoint source loading include agricultural chemicals, animal wastes, eroded soils and genetically engineered organisms.

Nonpoint pollution is characterized by highly variable loading, with rainfall and other environmental characteristics dominating the timing and magnitude of chemical transport. Chemicals are exported from their site of application to nearby streams and lakes by runoff and subsurface flow, leaching to ground water drift from aerial and ground application equipment, chemical dust transport and volatilization. Irrigation practices are known to enhance leaching of chemicals from soil, including applied chemicals, naturally occurring salts, selenium and other trace elements. Irrigation from contaminated water sources can introduce organic chemicals, salts, and nitrates to agroecosystems. Many of these chemicals are subsequently transported to surface water. Chemicals application in irrigation water (chemigation) raises similar concerns. (Meyer et al., 1992).

After careful consideration of the scientific, social, economic and environmental issues concerning agroecosystems and ecosystem health (Schaffer et al., 1988; Rapport, 1989), three assessment endpoints were identified that summarize the essence of the issues (Fig. 19). The assessment endpoints will be used to focus the interpretation of indicator data; they are quantifiable expression of environmental value that do not change over time, even when specific issuers do change. The assessment endpoints are sustainability, contamination of natural resources, and the quality of agricultural landscapes.

- *Contamination of natural resources* refers to alteration in the quality of air, water and soil by anthropogenically generated stressors that are inputs to or outputs from agroecosystems. Contamination of natural resources may, in turn, impact the structure or function of one or more agroecoystem component, from the biochemical to the ecosystem level. Contaminants can be found in the air, soil, water and biota of agroecoystems and may include air pollutants, agricultural chemicals, animal and municipal wastes, water pollutants and genetically-altered organisms.

- *Sustainability* refers to the capacity of a particular agroecosystm to maintain a level of commodity production that provides food and fiber for basic human needs and an economically viable livelihood for farmers, without jeopardizing the structural and functional components of the ecosystem.

- *Quality of the agricultural landscape* refers to the various ways in which the landscape matrix is modified or used over time for agricultural and non-agricultural purposes. Agricultural land use patterns modify the landscape in which they are developed and influence ecological processes. A vital characteristic of landscape modification is the extent to which the surrounding landscape can support populations of non crop vegetation and wildlife.

We discuss here the problem of agroecosystem contamination, and the next paragraph is devoted to the issues of agroecosystem sustainability and quality of agricultural landscape.

Assessing the spatial and temporal trends in the distribution and concentration of contaminants in agroecosystems is a complex undertaking because of existence of thousands of contaminant sources, spatial and temporal variability of source strengths, multi-media distribution of contaminants, and transformation reactions resulting in products different from the parent contaminants. Connel and Miller (1984) state that the objectives of environmental monitoring can be realized by focusing on two aspects: monitoring contaminants in different compartments of the environment , and monitoring the effects of contaminants on biota (Fig. 20). The physical and chemical monitoring of air, water and soil can provide information regarding the spatial and temporal trends of the contaminants, but monitoring of the ambient environment does not address issues pertaining to the bioavailability and fate of a contaminant, nor their potential for biological effects. Given these complexities, it is necessary to monitor both the abiotic and biotic component of ecosystem.

Based on the concepts of response functions method and resistance index as well as in case of radionuclides, the model of pesticides dynamics in the elementary ecosystem has been elaborated (Malkina-Pykh and Pykh, 1992).

As it has the structure similar to ^{90}Sr model, we will not give its detailed description, but pay special attention to simulation results.

Fig. 21-23 demonstrate pesticides dynamics in each unit of elementary ecosystems of various geographical zones.

Pesticides of the 3rd class persistence were chosen as an example (atrazin, etc.) It was applied annually to soils of various types in the amount of 3.3 kg/ha before the sowing of potato's leaving 30 years.

The rate of self-purification of soils is increasing from north to south, and the rate of self-purification of surface water is increasing from south to north. Also the period of stabilization of pesticides accumulation level is decreasing from north to south. The levels of stabilization of pesticides accumulation in soils are as follows: in middle taiga - 109,0 mg/kg, in southern taiga - 980; in forest steppe - 580; in steppe - 440; in subtropical 33,0 and in desert zone 27.0 (Fig. 21).

The rate of pesticides decomposition in plants, as well as in soils is increasing from north to south and the level of stabilization of pollutant's concentration are equal 0,72 mg/kg in the middle-taiga up to 0,025 mg/kg in the desert (Fig. 22).

The period, when the level of accumulation is stabilizing, is decreasing from more than 30 years in the middle taiga to 5 years in desert (Fig. 23)

The period, when the level of accumulation is stabilizing, is decreasing from more than 30 years in the middle taiga to 5 years in the desert.

As well as in case of radioactive contamination it is possible to calculate the resistance index of each unit of ecosystems towards the flow of pesticides contamination.

13. Example 3. Soil Organic Matter Dynamics and the Indicator of the Ecosystem Sustainability

One of the most important property of the ecosystems is sustainability (Fig. 10).

There are nearly as many definitions of sustainability as there are people writing about it. A sample is given in Fig. 24. We shall not discuss here the pressing concerns about the state of the environment and human welfare which have generated this focus on sustainability; these issues are fully expounded in the references cited in the table. The comprehensive expression of sustainability embodied in the first four definitions in Fig 24 is that sustainability embraces many concerns. These concerns may be grouped into three broad categories: ecology, economics and human equity.

Larson and Pierce (1991) recently presented an exhaustive discussion of the soil attributes that could be used in a minimum data set for the assessment of sustainability of the soil resource. They list a set of attributes and propose that the indices be grouped under the general term 'soil quality'. Soil organic matter, *sensu humus,* is included in the list and is identified as an attribute of particular significance.

It has been long recognized that cultivation practices significantly influence ecosystem structure and processes. Land use, however, is an important control over ecosystem properties, as is abundantly clear from the very large areas of cultivated land all over the world. The major effects of land use are to alter the dominant plant species, to reduce biological diversity, and to change the dynamics of soil organic matter, and potentially to have important feedbacks to atmospheric processes through gaseous, radioactive, and hydrologic interactions. Soil carbon is a good integrator of these process that has regional relevance. Soil carbon represents the long-term balance of productivity, decomposition, and erosion, and in semiarid regions is the single best indicator of ecosystem stability and sustainability (Burke et al., 1989; 1991). In addition, because of its interaction with global atmospheric carbon pools, it is important to large-scale "global change" studies (Schlesinger, 1990). Ameliorating the effects of global climate change on natural and intensively managed ecosystems will require considerably more knowledge than we currently possess about the responses of ecosystems to changes in temperature, moisture and natural and human-caused disturbance. Answering this question largely depends on our ability to assess how storage in the terrestrial ecosystem will change.

The particular significance of soil organic matter for soil fertility is that it influences so many different soil properties. It is simultaneously a source and a sink for nutrient elements which can form organic molecules (for example, with nitrogen, phosphorus and sulfur); it has charge properties which make it a site of ion exchange (often the most important one in the low-activity clay soils of the tropics); it has physical and chemical properties which facilitate aggregation with mineral particles, particularly clays, and in turn modify soil physical structure and influence soil water regimes; and it is a source of energy for the soil biota and thus influences many of the biologically mediated processes of soil. Thus, soil organic matter itself represents a set of attributes rather than an entity.

Soil organic matter should thus be targeted as a key resource because of its role in sustaining ecosystem function.

The roles of soil organic matter can be by-passed by agricultural practices - nutrients can be supplied by fertilization, water regimes can be enchanted by tillage or irrigation and acidity can be ameliorated by liming. Under these conditions, soil biological activities have a much reduced role to play in soil fertility maintenance. But these agricultural practices require an energy subsidy, which is supplied mainly from fossil-fuel sources. The importance of soil organic matter to sustainability lies predominantly in those circumstances where management based on fossil-fuel sources is either impossible or undesirable, which is the case in many tropical farming systems. There is also a question as to the relative sustainability of cropping systems based on soil organic matte compared to those that are petroleum-based, particularly in terms of energy output/input ratios.

The discussion above has established a number of criteria for using soil organic matter measurements as an index of sustainability. In the first place, the index should be able to show with some sensitivity the variability in organic matter status. At the same time, it should be indicative of the significance to soil fertility of any observed changes.

Using response functions method, the model of humus (soil organic matter) dynamics in the natural as well as in the land-used ecosystems has been elaborated. Also this model includes the changes of humus content resulted from erosion and global climate change (Malkina -Pykh and Pykh 1994; Pykh and Malkina-Pykh 1994).

Soil organic matter, a major source of natural as well as the agricultural ecosystems stability, is controlled by many factors that have complex interactions.

Thus the problem is not especially the definition of humus balance as the result of the common impact of various factors, but the elucidation of values of the main components of humus balance in the concrete soil and geographical conditions as well as land use practices.

Humus formation is the process of formation and functioning of the soil humus system, consisting of the set of stages and including the set of elementary processes of humus formation. The following elementary processes of humus formation can be singled out: decomposition of plant debris, the process of humus formation itself and the process of humus mineralization (decomposition).

The quantitative measure of decomposed plant debris incorporated into humus matter is the humufication coefficient (K_h) which is equal to that part (may be in percentage) of plant carbon, included into soil humus matter after their full decomposition. The quantitative measure of soil humus decomposition is the coefficient of mineralization K_m, which reflects that part of soil organic matter, distructed annually.

The dynamics of soil organic matter in the climax ecosystem, where the amount of the decomposed humus is equal to the amount of newly formed humus, is describing in the following form: $dH = K_h \cdot B - K_m \cdot H = 0; H = K_h \cdot B / K_m$, where dH is the annual accumulation of humus matter, B is the annual plant input, K_h and K_m are the coefficients of plant debris humification and humus mineralization subsequently, H is the modern humus amount.

In the proposed model of soil humus formation we do not examine the process of plant debris decomposition, but only those processes resulted directly in the amount of humus such as humification and mineralization as the combination of those external driving parameters, responsible for the dynamics of the object under study. The spatial unit of the given model is the elementary (automorphic) ecosystem in eluvial position near watersheds, from which the active transfer occur. The time step of the model equals one year.

On the basis of precise studying the existing literature on the problem of humus formation, we examine the main driving parameters of the environment responsible for the process under study. They are as follows: plant debris, microorganisms, soil texture, moisture and temperature, the ratio of humic/fluvic acids, calcium cations content and soil pH, soil nitrogen uptake by plants.

On the basis of the given main driving parameters of humus formation, the general model of humus formation in the natural ecosystems (elementary, eluvial) under the typical plant cover is described as follows:

$$H = KHUM \cdot B / KMIN$$

$$KMIN = f_1^m(UK) \cdot f_2^m(GL) \cdot f_3^m(pH) \cdot f_4^m(NO) \cdot f_5^m(HF) \cdot f_6^m(N)$$

$$KHUM = f_7^h(UK) \cdot f_8^h(GL) \cdot f_9^h(pH) \cdot f_{10}^h(AC) \cdot f_{11}^h(Ca)$$

$$f_j^{h,m}(x_j) = \alpha_j \cdot x_j^{b_j} \cdot \exp(-c_j \cdot (\frac{x_j}{x_{\max} - x_j})) \qquad j = 1,7$$

$$f_j^m(x_j) = 1.0 - \alpha_j (1.0 - \exp(-b_j \cdot x_j))^{C_j} \qquad j = 2,3,5$$

$$f_j^m(x_j) = \frac{\alpha_j}{1.0 + \exp(b_j - c_j \cdot x_j)} \qquad j = 4,6$$

$$f_j^h(x_j) = \frac{\alpha_j}{1.0 + \exp(b_j - c_j \cdot x_j)} \qquad j = 8,..11, \tag{13.1}$$

where H is humus content in soil of natural ecosystem under the natural plant cover (tons/hectare), $KHUM$ is the humification coefficient, $KMIN$ is the mineralization coefficient, $f_j^{h,m}$ are the partial response functions of humification and mineralization processes to the values of driving parameters of humus formation, B is the annual plant debris (tons/hectare), UK is the moistening index, GL is the clay content (%), pH is the soil acidity, HF is the ratio of humic and fulfic acids, AC is the amount of actinomycetes in soil (ml/ g), Ca is the calcium cations content (mg eqv/100 g), NO is the amount of proactinomycetes (ths/g), N is the soil nitrogen up-take by plants (kg/hectare), α_j, b_j, c_j are parameters for evaluation.

Evaluation of model's (13.1) parameters was done with a wide range of experimental data about humus content and driving parameters of humus formation for 25 soil types (Table 3).

In our model we examine the soil layer of 0-100 cm, i.e. the layer impacted by the land-use. As the model is done for the soils of CIS, we use the data of humus content of Russian scientists.

Sometimes for practical uses it is necessary to prognoses not only the dynamics of humus storage (tons/hectare), but also the percentage content of humus (%). In that case we use the conversion equation

$$G = H / 10^2 \cdot h \cdot g \qquad (13.2)$$

where H is the storage of humus (tons/hectare), h is the thickness of soil layer (m), g is the soil density ($\mathrm{g} / \mathrm{cm}^3$), G is humus content (%).

The evaluation of parameters of the model of humus formation in the natural ecosystems was done as follows:

$$\sum_{i=1}^{N} (H_{\mathrm{mod}}(KHUM, KMIN) - H_{\mathrm{exp}})^2 \Rightarrow \min, \qquad (13.3)$$

where H_{exp} are the experimental data of humus content (% or tons/hectare), H_{mod} are the model values of humus content, calculating from (13.1), i is the number of sets of experimental data, j is the number of parameters, $N > j$.

The precision of the evaluation of parameters is not less then 90%. The view of partial response functions of mineralization and humification processes are given in Fig. 25 and 26.

We describe and examine in the model the following types of land-use practices that have the greatest impact on the process of humus accumulation:

1. Fertilizing (mineral and manure); 2. Liming; 3. Irrigation.

The general impacts resulted from various types of soil cultivation is taken into account in the model. Such management practices as drainage and gypsum of soils are beyond the study.

It's evident that the application of sufficient amount of manure resulted the increase of humus content in soil of various geographical zones as well as the extension of humic/fulvic acids ratio. Although, it was observed that only the long-term manure application, not less then 10-12 years, resulted the reliable increase of humus content.

Thus the variations of humic / fulvic acids ratio as depending on the date and dose of manure applications is describing in the following way:

$$C^{h/f}(D,t) = A + B \cdot (1.0 - \exp(-g \cdot D \cdot t)), \qquad (13.4)$$

where $C^{h/f}$ is the humic / fulvic acids ratio, A and B are the initial and maximum values of this ratio depending on soil type, D is the dose of manure applied (tons / ha per year), t is the period of manure application (years), g is parameter for evaluation. The data taken from literature cited above on various applied doses of manure on various soil types were used for parameters' evaluation. The view of function (13.4) as well as parameters' values are given in Fig. 27.

The added matter for humification due to the direct application of manure is not proportional to the amount of applied manure, and this dependence is described as follows:

$$dB(D) = a \cdot D^{-b} \cdot d^{-c \cdot D}, \qquad (13.5)$$

where $dB(D)$ is the added matter for humification in soil (tons/ha dry matter per 1 ton of manure), D is the dose of applied manure (tons/ha per year), a, b, c, d are parameters. The view of function (13.5) as well as parameters values are given in Fig. 28.

Thus, the continued use of ammonium fertilizers, and especially of ammonium sulfate has, in the absence of remedial lime applications, led to severe soil acidification in many weakly buffered soils.

Liming of acid soils improves their physical and chemical properties, create the favorable conditions for humus accumulation. Although mineral soils commonly contain only a few per cent of humus carbon, the humic substances have a very large influence on the cation exchange capacity of the soils, often contributing half or more. It is true in the case of acid buffer capacity as well as in the case of alkaline buffer capacity. The function of alkaline buffer capacity is described as follows:

$$f_s(HU) = 1.0 - a(1.0 - \exp(-b \cdot HU))^c, \qquad (13.6)$$

where $f_s(HU)$ is the function of inhibiting effect of soil buffer capacity, HU is the humus content (%), a, b, c are parameters.

The dependence of the new pH value on the amount of applied lime has the following form

$$pH(Ca) = pH_{\max}(1.0 - \exp(-g \cdot f_s(HU) \cdot CaCO_3)) + pH_0, \qquad (13.7)$$

where $pH_{\max}$ is the maximum possible pH value which could be reached taking into account that when pH = 6.0 the liming is already forbidden, $CaCO_3$ is the amount of applied lime (t/ha per year), pH_0 is the initial pH value. The view of functions (13.6) and (13.7) as well as the parameters' values are given in Fig. 29, 30.

Now let us examine the process of soil acidification resulted by the application of nitrogen fertilizers. In this case the soil buffer function is similar to (13.6) except the parameters' values

$$f_a(HU) = 1.0 - a(1.0 - \exp(-b \cdot HU))^C \qquad (\ 13.8\ )$$

Then the function of acidifying impact of nitrogen fertilizers is presented in the following form:

$$f_s(AZ) = \alpha\ (\frac{1.0}{a + \exp(b - c \cdot AZ)} - d), \qquad (\ 13.9\ )$$

where AZ is the amount of the applied mineral fertilizers (kg/ha per year), α, a, b, c, d are parameters.

In case if after the lime application the mineral fertilizers are not applied then the natural acidification of soil takes place, and in this case the rate of this process depends on the current pH value: the higher is the current pH value the higher is the rate of acidification. Also in the case of mineral fertilizers ' application the rate of acidification is also depended on the current pH value. Function $f_s(pH)$ is similar to $f_s(AZ)$ except the parameters' values.

The general view of the function of soil acidification under the impact of the mineral fertilizers is following:

$$pH(t) = pH_0 \cdot \exp(-g \cdot f_a(HU) \cdot f_s(AZ) \cdot f_s(pH) \cdot t). \qquad (13.10)$$

The view of functions (13.8), (13.9), (13.10) and $f_s(pH)$ as well as parameters' values are given in Fig. 31-34 respectively.

The introduction of improved methods of farming can of course increase soil organic matter The accumulation of organic matter under improved pasture is an example. Definitely the annual input of plant material is increasing with the increasing of yield, but the ratio of these components is narrowing also with the increase of yield. In the given submodel we examine the following groups of agricultural plants: 1. winter and spring crops; 2. perennial grasses (green bulk); 3. potato. The dependence of the roots and reaps remains on the yield is as following:

$$B_r(B) = B_m(1.0 - d^{-l \cdot B}), \qquad (13.11)$$

where $B_r(B)$ is the amount of root and reap remains (metric centner/ha), B_m is the maximum possible value of $B_r(B)$ for the given crop sort on the given soil type, B is the average yield of the given crop (metric centner/ha), d, l are parameters. The view of function (13.11) for various crop types as well as the parameters values are given in Fig. 35.

The additional amount of yield results from the application of various dosages of mineral nutrition is described in submodel in the following form:

$$dB(AZ) = alfa \cdot AZ^{b} \cdot d^{(-c(\frac{AZ}{AZ_{\max} - AZ})^{g})}, \qquad (13.12)$$

where $dB(AZ)$ is the additional yield (% of the yield without mineral fertilizers' application), AZ is the amount of applied nitrogen fertilizers (kg/ha per year), $alfa$, b, c, d, $AZ_{\max}$ are the parameters for evaluation, $alfa$ is the index reflecting the additional impact of the organic fertilizers on the crop yield. The view of function (13.12) and parameters' values for various crop types are given in Fig. 36.

The added up-take of soil nitrogen by plants (added nitrogen interaction) as resulted from the application of various dosages of mineral fertilizers comparing with the soils without fertilizing is described in the following form:

$$dN(AZ) = AZ_{\max}(1.0 - \exp(-g \cdot \frac{AZ}{f(HU)})), \qquad (13.13)$$

where $dN(AZ)$ is the added up-take of soil nitrogen resulted from the application of various dosages of mineral fertilizers (% of the unfertilized soils), AZ is the dosages of applied mineral fertilizes (kg/ha per year), $AZ_{\max}, g$ are parameters, $f(HU)$ is the function of soil buffer capacity towards the acidification effect of mineral fertilizers which is described as follows:

$$f(HU) = \alpha \cdot (\frac{1.0}{a + \exp(b - c \cdot HU)} - d), \qquad (13.14)$$

where HU is the soil humus content (%), α, a, b, c, d are parameters. The view of functions (13.13) and (13.14) as well as parameters' values are given in Fig. 37,38.

The changes of humus content because of irrigation can be positive as well as negative. First of all it depends greatly on the initial humic characteristics and closely connected with the regime of irrigation and quality of irrigation water.

The varying of ration $C^{h/f}$ as depending on the quality of irrigation water is describing as follows:

$$\begin{aligned} &C^{h/f}\ (t) = C_0{}^{h/f} \cdot \exp(-b \cdot \ln(t)), && k < 1 \\ &C^{h/f}(t) = const, && k = 1\ , \\ &C^{h/f(t)} = C_0^{h/f} + C_{\max}^{h/f}(1.0 - \exp(-c \cdot \ln(t))), && k > 1 \end{aligned} \qquad (13.15)$$

where $C_0^{h/f}$ is the initial ratio of humic and fulvic acids, $C_{\max}^{h/f}$, b, c are parameters, k is the quality of irrigation water, t is the irrigation period (years). So on it is supposed that irrigation with the water of low quality results the processes of salinization or/and alkalization and the ratio humic/fulvic acids is decreasing. The irrigation with the water of medium quality remains this ratio constant, and the irrigation with the water of high quality could increase this ratio. The view of functions (13.15) and the values of parameters are given in Fig. 39.

Variations of calcium content under the impact of irrigation is described by the following equation:

$$Ca(t) = Ca_0 \exp(-b(k) \cdot \ln(t)), \qquad (13.16)$$

where $Ca(t)$ and Ca_0 are the current and initial calcium contents in soil (mg eqv/ 100 g), $b(k)$ is the parameter depending on the irrigation water quality,

t is time (years). The view of function (13.16) and parameters values are given in Fig. 40.

The dependence of soil pH dynamics on irrigation water quality is given in the following form:

$$pH(t) = A - \alpha(t+a)^{b} \exp(-c\frac{t}{t_{\max} - t}), \qquad (13.17)$$

where $pH(t)$ is the current value of soil pH, α, a, b and c are parameters, depending on the soil properties and quality of irrigation water, t is time (years) and $t_{\max}$ is the forecasting period(years). The view of function (13.17) and values of parameters are given in Fig. 41.

Erosion removal of humus following agricultural land use is probably very important. Sometimes, most of humus lost from disturbed soils is lost through erosion rather then increased oxidation. Thus, the annual amount of soil losses resulted from water erosion is calculated as follows:

$$\begin{aligned}
&ER = ER\max \cdot f_1^e(EI) \cdot f_2^e(KS) \cdot f_3^e(LS) \cdot f_4^e(CUL) \cdot f_5^e(AGR) \\
&f_j^e(x_j = \alpha_j(\frac{1.0}{a_j + \exp(b_j - c_j x_j)} - d_j) \qquad\qquad j = 1..4 \\
&f_5^e(AGR) = 1.0 - \alpha_5 \exp(1.0 - \exp(-b_5 \cdot AGR))^{C_5} \\
&ER = ER + SNEG \cdot K_{AGR},
\end{aligned} \qquad (13.18)$$

where ER is the annual soil loss (tons/ha per year), $ER_{\max}$ is the maximum possible soil loss when all conditions are unfavorable, EI, KS, LS are the erosivity of the rainfall, erodibility of the soil and slope index, CUL is the index of soil protective properties of crops, AGR is the index of effectiveness of conservation measures evaluating by the special scale, $SNEG$ is the soil wash-off by the melting snow water depending on the layer of surface runoff (tons/ha per year), K_{AGR} - is the cropping system index, α_j, a_j, b_j, c_j, d_j are parameters, $j = 1,..,5$.

The views of partial response functions of water erosion's factors from the model (13.18) as well as parameters' values are given in Fig. 42.

In southern regions of our country soil loss resulted from wind erosion is essential. It occurs when the wind speed exceeds the level of soil resistance. Thus the submodel for soil loss resulted from wind erosion is given in the following form:

$$DEFL = DEFL\max \cdot f_1^d(CL) \cdot f_2^d(S) \cdot f_3^d(CUL) \cdot f_4^d(AGR)$$

$$f_1^d(CL) = \alpha_1 (\frac{1.0}{a_1 + \exp(b_1 - c_1 \cdot CL)_1} - d_1) \qquad (13.19)$$

$$f_2^d(S) = 1.0 - \alpha_2 (1.0 - \exp(-b_2 \cdot S))^{C_2},$$

where $DEFL$ is the soil loss resulted from wind erosion (tons/ha per year), $DEFL_{\max}$ is the maximum soul loss when all factors are unfavorable, CL is the climatic factor of wind erosion, S is the soil cohesioness, CUL and AGR are the indices of crop protective properties and conservation measures., describing similar to the submodel (13.18), α_j, a_j, b_j, c_j, d_j are parameters, $j = 1,2$.

The view of partial response functions of submodel (13.19) as well as parameters values are given in Fig. 43.

Many authors predict that in the nearest future the increasing humus losses can cause the ecological disaster. It can appear because the soil humus is the base of soil fertility on one hand, and the key link of biosphere stability on the other. Humus losses cause the increasing of CO_2 concentration in the atmosphere, coupling with the " green -house effect" and climate warming.

When examining the changes in humus content resulted from Global Climate Change we use the scenario of changes of temperature and precipitation from (Velitchko, 1992).

In general the impacts of global climate change on humus dynamics can appear through direct and indirect ones. The indirect impact is connected with the shifts of natural vegetation and amount of plant debris derived from above and below ground sources. The direct impact is resulted from the changing of thermal and hydrological conditions and thus appears through the moistening index on the balance of humufication and humus mineralization processes The number and species composition of microorganisms providing the processes of humification and mineralization are also changing. Such properties included into our model as soil pH, clay and calcium ions contents are less influenced with global climate change.

Simulation experiments. The extent of soil organic matter depletion has been shown to depend upon the same variables as those controlling soil organic matter formation, with losses strongly dependent on management regime and regional location.

A set of computer experiments were done on the given model and the results are presented below.

Sod - podzolic soils. The results of computer experiments for sod-podzolic soils are given in Fig. 44. The humus dynamics during 100 years were examined resulting from the following management regimes:

1. -Tilled crop production (potato).
- Subsurface tilled soil.
-Mineral fertilizer application - 100 kg per hectare per year.

2. Tilled crop production (potato).
- Mouldboard cultivation.
- Mineral fertilizer application - 100 kg per hectare per year.
- Manure application - 20 metric tons per hectare per year.

3. Cereal crop production.
- Mouldboard cultivation.
- Mineral fertilizer application - 100 kg per hectare per year.
- Manure application - 20 metric tons per hectare per year.

4. Perennial grasses production.
- Manure application - 20 metric tons per hectare per year.

5. Tilled crop production.
- Subsurface tilled soil.
- Mineral fertilizer application - 200 kg per hectare per year.
- Lime application - 12 metric tons per hectare , single application after 35 years of land use.

6. Cereal crop production.
- Mouldboard cultivation.
- Mineral fertilizer application - 120 kg per hectare per year.
- Lime application - 12 metric tons per hectare , single application after 35 years of land use.

In ploughed sod-podzolic soils as compared with virgin land the conditions of humus formation are improved that resulting in the humus content increased. As calculations show, when producing the tilled crops with the application of only mineral fertilizer, humus content declines from 3.4 to 2.1 % (see curve 1), but when even the single liming is provided (see curve 5) humus content can be kept practically on the initial level.

Manure application increases the humus content even when the tilled crops are cultivated (see curve 2), and cultivation of cereal with application of manure and mineral fertilizers can increase humus content significantly - from 3.4 to 5.1% (see curve 3). Also humus content can increase from 3.4 up to 4.8 % when cultivating the cereal crop with application only mineral fertilizer, but with liming (see curve 6).

When producing perennial grasses with annual application of manure , humus content in sod-podzolic soils increases twice.

Gray forest soils. The results of computer experiments for gray forest soils are given in Fig. 45. As well as with sod -podzolic, for gray forest soils humus dynamics for 100 years of cultivation was examined with the various management regimes:

1. Perennial grasses production.

- Manure application - 20 metric tons per hectare per year.

2. Cereal crop production.

- Mouldboard cultivation.
- Mineral fertilizer application - 120 kg per hectare per year.
- Manure application - 20 metric tons per hectare per year.

3. Tilled crop production (potato).

- Mouldboard cultivation.
- Mineral fertilizer application - 120 kg per hectare per year.
- Manure application - 20 metric tons per hectare per year.

4. Tilled crop production.

- Mouldboard cultivation.
- Mineral fertilizer application - 200 kg per hectare per year.
- Manure application - 20 metric tons per hectare per year.
- Lime application - 12 metric tons per hectare , single application after 35 years of land use.

Comparing with sod-podzolic soils, gray forest soil dynamics resulted from various land-use practices is different. Gray forest soil is less responsive to manure applications.

As calculations show, cultivating of perennial grasses with annual manure application results in humus content increase, but only up to 5.3% from 3.8% of initial content (see curve 1).

When producing cereals with annual applications of mineral and organic fertilizers the humus content keeps on the initial level practically (see curve 2), and producing of tilled crops with the same fertilizers' application results in humus content decrease up to 2.2% (see curve 3). But, if the lime application is provided when producing tilled crops, then humus content can be back nearly to the initial level - 3.0% (see curve 4).

Typical chernozem. The results of simulation experiments with typical chernozem are given in Fig. 46. In experiments, the following scenario of agricultural land-use have been simulated.

1. - Cereal crops production.
- Mineral fertilizer application - 120 kg per hectare per year.
- Organic fertilizer application - 20 metric tons per hectare per year.
- Subsurface tilled soils.
- Without irrigation.

2. The same type of management as in (1),
but irrigation with the water of low quality.

3. The same type of management as in (1),
but irrigation with water of medium quality.

4. The same type of management as in (1),
but irrigation with water of high quality.

As calculations show, when ploughing chernozem the humus content is noticeably reduced from 20 to 65% of the initial value. This is primarily due to considerable reduction of the amount of humus sources in soil (for 5-6 times) and increase of mineralization of organic substances because of cultivation.

In this case during the first 10-15 years humus content is rapidly decreasing because of fast disintegration of labile forms of organic substances, however subsequently this decrease is retarding and humus content is stabilizing at a new level.

In case of chernozem growing cereal crops even with using mineral and organic fertilizers leads to decreasing humus content in them by 45% - from 8.0 up to 4.8 % (see curve 1).

As seen from calculations, irrigation exerts unambiguous effect on typical chernozem. In this case much depends on the quality of irrigation water. Irrigation with low-quality water results in alkalization of soils. Then humus content is considerably lowered as compared with the initial value - up to 2 % (see curve 2). Irrigation with water of medium quality leads practically to the same reduction of humus in chenozems as in the first variant of land use (see curve 3). At the same time when irrigating with high-quality water, humus content in them can even increase up to 9.5 % from the initial value (see curve 4).

On the whole the calculations indicate that the modeling of humus dynamics in chernozem for different variant of land-use practices, as well as in the previous cases, demonstrates high potentialities of predictability which are proved by the experimental data.

Chestnut soils. The results of computer simulations for chestnut soils are given in Fig. 47. The following scenario of land-use practices were examined.

1.Cereal crop production.
- Subsurface tilled soil.
- Mineral fertilizer application - 120 kg per hectare per year.
- Manure application - 20 metric tons per hectare per year.
- Irrigation with water of low quality that leads to the alkalization and degradation of soils.

2. The same management type as in (1) ,
   but with irrigation of high-quality water.

3. The same type of management as in (1),
   but without irrigation.

As our calculations show the largest humus losses appear when cereal crop production with mineral fertilizer application of 120 kg/ha per year and manure application of 20 metric tons/ha per year annually without irrigation as well as with the irrigation of low-quality water. The losses amount to 3.1% to 1.1%. In case of irrigation with the water of high quality humus losses are also appear, but less - from 3.1% up to 2.8%, i.e. it can be assumed practically that humus content keeps on the initial level.

Also important that in various soil types humus losses due to erosion equal the specific values, because the origin and intensification of erosion have the distinct local character.

In addition to calculations of various scenario of land use management on various soil types, the set of computer experiments on the varying of humus content resulted from global climate change were provided. The results of calculations are given on Fig. 48. The principal trends of the soil humus dynamics in situation of global climate change are also well correlated with the existing hypothesis.

14. Example 4. Phenological Development as an Indicator of Biological Productivity.

The integrity of ecosystems is reflected in the fact that its different components have in some extent the common reaction to the whole complex of abiotic factors. That is why the phenological dates (flowering, ripening, etc.) can serve as an indicators for some other processes in the ecosystems. For example, we can speak about the expected biological productivity of the other species in the ecosystem but not that for which the phenological dates have been registered. The studies have been provided to elucidate the correlation between the flowering dates of currants (*Ribes hispidilum*), bird-cherry tree (*Padus avinum*) and dog-rose (*Rosa acicularis*) and the annual increasing of ring width of Siberian larch (*Larix sibirica*) (Malafeev et al., 1994). The results demonstrate that the dates of phenological phases are better indicators of the expected biological productivity then any of the meteorological characteristics.

On the base of response function method, the model of ontogenesis in higher plants has been elaborated. The model includes submodels of phenological development, biomass growth and the distribution of assimilates.

Submodel of phenological development. Phenological development of plants is measured by the days of duration of every phenological phase and/or interphase period. For the formal description of phenological phases we use the scale of biological time, which is (for the given interphase period) the segment of the real axis $[0,\bar{M}]$ (Malkina 1986). Here $\bar{M}$ corresponds to the biological age at which the plants leave the given interphase period. We determine the $\bar{M}$ values during the simulation of phenological development using standardized response functions. In this case, as we show below, the $\bar{M}$ values are of some actual biological meaning; they are numerically equal to the minimum physical time of the given interphase period (Malkina and Pykh,1988). Based on the existing hypotheses of higher plant development, $\bar{M}$ is a genetically stipulated characteristic of a species, which is realized when the optimum values of all environmental factors are present (Chailakhyan, 1975).

Only the environmental factors are analyzed. In particular, in our model the effect of pre-evolution is included, but not that of the growth processes or hormonal substances on the phenological development of plants. This restriction is primarily due to the fact that there are no sufficiently reliable experimental data on the nature of the impact of these factors on the plant development. It must be emphasized that the entire sowing process rather then any single plant is taken into consideration. This means that all values comprising the model are of an average pattern.

Thus, based on the existing division of the vegetative period into phenological phases for principal agricultural crops, the model accepts the following differentiation of this period into phenological phases and the respective interphase periods: 0, sowing; 1, sprouting; 2, flower budding; 3, flowering; 4, seed filling; 5, milky ripeness; 6, waxy ripeness; 7, complete ripeness (Chailakhyan et al., 1982). By the interphase period we mean the time beginning with the moment of complete onset of the first phenological phase and ending with the complete onset of the second one.

Let the biological time of a plant, reached to a certain day of $i-$interphase period be expressed as $M(l)$. It is clear that $M(l)$ varies within 0 and $\bar{M}$. Then, $M(l)$ is controlled by the impact of a set of environmental factors $x_1(l),\dots,x_n(l)$, where n is the number of factors taken into account. In the model we suppose them to be: t , minimum daily air temperature (^0C); W, soil humidity (per cent of the lowest moisture capacity, %LMC); L, length of the day (h) (Malkina, 1986).

It should be realized that most probably the factors controlling the development of plants involved interrelate mechanisms of thermal, photoperiodic and other factors. However, in this case, when elaborating our model, we admit that the regulating factors are independent. This assumption perhaps restricts slightly the area to which the model can be applied, but it greatly simplifies the model.

As follows from the accepted hypotheses, the impact of the environmental factors $x_1(l),\dots,x_n(l)$ should naturally be considered by using multiplicative concept. Thus, we derive the following function of biological age on the $i-$interphase period:

$$M_i(l,x)=\sum_{K=1}^{l}\prod_{j=1}^{n}f_{ij}[x_j(k)] \qquad (\ 14.1\ )$$

where f_j is the unimodal response function to j factor, l is the number of days. Unimodal response functions will be regarded as standardized so that within the area of definition the following conditions should be satisfied:

$$\max_{x_j} f_j(x_j^{opt}) = 1.0. \qquad (14.2)$$

It is evident that the values of x_j providing the maximum for the function f_j are equal to the optimum values of the factors x_j^{opt}. Thus, this optimal values of all factors the biological time so chosen coincides with the chronological time, and any deviation in the value of the factors from the optimal ones retards the development. Simultaneously, we derive an equation to determine the time l for the duration of the interphase period i at any values of the factors:

$$\sum_{K=1}^{l} \prod_{j=1}^{n} f_{ij}[\alpha_j^i, x_j^i(k)] = \bar{M}_i, \qquad (14.3)$$

where α_j^i is the parameters' vector. We choose the indicies of the phases and interphase periods in such a way that $\bar{M}_i$ indicates the minimum duration of the interphase period and M_i determines the biological age on the $i-$interphase period.

The next problem is the actual choice of the functions f_j. Based on the analysis of data in literature (Robertson 1968; Stepanova 1985), the main regulatory factors of the impact of complexes of environmental factors upon phase-to-phase transition and upon the rate of the duration of the interphase periods were established: maximum and minimum daily air temperature and soil humidity regulate the onset of the 1st, 4th, 5th, 6th and 7th phases, the onset of the 3rd phase is determined by the maximum and minimum daily air temperature and photoperiod; the onset of the 2nd phase is affected by all four mentioned factors.

The development of plants is most essentially influenced by the maximum and minimum daily air temperature (Angus et al., 1980; 1981). While working with the model, we analyzed a great number of various functions, and after a series of computer simulations we identified two types of functions, yielding the best results in the evaluation of the values of the parameters for the submodel of phenological development.:

$$f(x) = \alpha x^b \exp(-c\frac{x^\gamma}{x_m - x}) \tag{ 14.4}$$

$$f(x) = \alpha x^b \exp[-c(\frac{x}{x_m - x})^\gamma] \tag{ 14.5}$$

We have omitted the indices in order to simplify the form. x means T_{ik} or t_{ik};α, b, c, γ are parameters; and x_m is the upper threshold temperature value. Equation (14.4) was employed for the 1st, 5th, 6th and 7th interphase periods and equation(14.5) was used for the others.

The rate of the onset of all phenological phases except flower budding is, in addition to temperature, greatly affected by soil humidity. Let us express the latter as W, comprising the per cent of the lowest moisture capacity (% LMC) in the layer containing the bulk mass of roots, where LMC is the maximum amount of capillary-suspended water, retained by the soil after gravitation water completely runs off. To identify the $f(W)$ response function in terms of soil humidity we select the following equation:

$$f(x) = \alpha(W - W_w)^b \exp(-c\frac{W}{W_m - W}), \qquad (14.6)$$

where W_w (% LMC) is the wilting point, W_m is the upper threshold value of soil humidity and α, b, c are the parameters for evaluation. We should We should like to note that all of the values mentioned above depend on the interphase period.

The duration of the 2nd and 3rd interphase periods depend on day length L (h). For these periods the following form of the response function in terms of the photoperiod duration was accepted:

$$f(L) = \exp[-c(L_{opt} - L)^2], \qquad (14.7)$$

where L_{opt} (h) is the optimal day length for the development of the species at the given stage and c is the parameter for evaluation.

Submodels of biomass growth and distribution of assimilates. The submodels of biomass growth and distribution of assimilates are entered into the general model from the day of sprouting. In the model described, an allowance is made for the effect of the following factors on biomass growth of plants: photosynthetic active radiation (PAR), maximum, minimum and average daily air temperatures, soil humidity, content of available nitrogen in soil, and stages of phenological development. The step of the model is equal to 1 day.

In the following derivations $B(k)$ denotes the biomass of plants from a unit of crop area on the k th day, and $\Delta B(k+1)$ denotes the increase in biomass during $(k+1)$th day:

$$B(k+1) = B(k) + \Delta B(k+1). \quad (14.8)$$

According to the conventional approach (Biklele et al., 1980), it is assumed that the daily increase ΔB is formed due to photosynthesis F, respiration for growth R_1 and respiration for maintaining structural biomass R_2:

$$\Delta B(k) = d[F(k) - R_1(k) - R_2(k)], \quad (14.9)$$

where d is the coefficient of "transition" from absorbed CO_2 to dry weight in the process of photosynthesis (g/g).

Photosynthesis depends respectively on the photosynthetically active radiation per day $(kcal / m^2 \cdot day)$, soil humidity in the root layer W (% LMC), average daily air temperature $T_a(^0C)$, and content of available nitrogen in soil, $N(mg / kg)$, i.e.:

$$F = f_1(I) \cdot f_2(W) \cdot f_3(T_a) \cdot f_4(N) \quad (14.10)$$

where $f_j, j = 1,\ldots,4$, is the response function to a corresponding factor. Growth respiration according to the model depends on the photosynthesis F and maximum daily air temperature $T(^0C)$:

$$R_1 = \eta F f_5(T), \quad (14.11)$$

where η is the coefficient of growth respiration (g/g) (Barnes and Hole 1978). Maintaining respiration is a function of total biomass B, and maximum and minimum daily air temperature, T and t:

$$R_2 = \varepsilon B f_5(T) f_6(t), \qquad (14.12)$$

where ε is the coefficient of maintaining respiration (g/g per day) (Barnes and Hole, 1978).

By substituting Eqs. in, the principal equation of biomass growth is obtained:

$$\Delta B(k+1) = d[f_1 f_2 f_3 f_4 (1-\eta f_5) - \varepsilon B(k) f_5 f_6]. \qquad (14.13)$$

As result of performing simulation experiments, we selected the following function of dependence of the rate of photosynthesis on PAR $(kcal / m^2 \cdot day)$:

$$f_1(I) = f_1(I) = \alpha_1 \frac{I(1-\exp(c_1 B_s^{\gamma_1})}{I+b_1}, \qquad (14.14)$$

where B_s is the above-ground biomass of the plants $(g / m^2), I$ is incident PAR, α_1 is the maximum potential output of photosynthesis of a given species $(g / m^2 \cdot day), b_1, c_1, \gamma_1$ are the parameters for evaluation. In the functions of dependence of photosynthetic rate on light conditions, there are usually indices of the photosynthetic area, area of leaves, index of the leaves' surface area, or various combinations of these. We established that the inclusion of the above-ground biomass index in the model does not impair the predictive potential of it, but at the same time considerably simplifies the completion of the submodels of growth and distribution of assimilates.

The response function to soil humidity was selected as follows:

$$f_2(W) = \alpha_2 (W - W_w)^{b_2} \exp(-c_2 \frac{W}{W_m - W}), \qquad (14.15)$$

where W_w is the humidity of steady wilting (% LMC) and W_m is the upper value of soil humidity at which the normal functioning of the plant is suppressed.

For the remaining response functions the following form of dependence is taken:

$$f_j(x) = \alpha_j x_j^{b_j} \exp(-c_j \frac{x_j}{x_{m_j} - x_j}), \qquad (14.16)$$

where x_j is the value of corresponding factor: T_a, N, T or $t; x_m$ is the maximum biologically permissible, and the threshold value of the factor; α_j, b_j, c_j are the parameters for evaluation, $j = 3,4,5,6$.

To complete the model, as follows from Eq. 14.3, it is necessary to supply equations which describe the distribution of assimilates between the aboveground parts of the plants and the roots. In those, account was taken mainly of the mechanism of competitive interaction between the nitrogen and the moisture in the soil and the assimilates accumulated per day (the step of the model) (Pykh and Malkina, 1986; 1989).:

$$\frac{\Delta B_s}{\Delta B_r} = \frac{B_s(k)[(N(k)/a_1)(W(k)/a_2)]^{\gamma_2}}{B_r(k)[\Delta B(k+1)/\alpha_3]^{\gamma_3}}, \qquad (14.17)$$

where ΔB_s is the increase of biomass of aboveground plant parts $(g/m^2 \cdot day)$, ΔB_r is the increase of biomass of roots $(g/m^2 \cdot day)$ during the $(k+1)$th day, N is the content of available nitrogen in soil (mg/kg) and W is the humidity of the root layer of the soil (% LMC). Parameters $a_1, a_2, a_3, \gamma_2, \gamma_3$ are determined during the identification.

In this way it becomes clear that the part of the plant existing under relatively worse conditions actively competes with other part of the plant to gain metabolites which limit the synthesis of the constitutional substances. In addition, the model was supplemented with the additional condition that function is used only until the onset of ripening, i.e. the stage of milky ripeness (Charles-Edwards, 1976; Reynolds and Thornley, 1982). Later on, the value of the root biomass remains constant, i.e.

$$\begin{aligned} &B_{ri} = const \\ &B_{si} = B_i - B_{ri}, \qquad i = 6,7' \end{aligned} \qquad (14.18)$$

where i is the number of the interphase period.

The dynamics of the reproductive process can serve as species and sorting characteristics of plants. However, one can identify certain general factors that allow for the construction of a model of the reproductive process for a rather large class of plant species. The moment when the seed filling begins is taken as the onset of the reproductive period in our model. The function of the seed biomass increment during the day is as follows:

$$\Delta G(k+1) = f_7(W)G(k)\{\xi\Delta B_s(k+1) + \omega[B_s(k) - G(k)]^{\gamma_4}\}, \qquad (14.19)$$

where ΔG is the seed biomass increment during the $(k+1)$th day $(g/m^2 \cdot day), G$ is the seed biomass at the kth day $(g/m^2 \cdot day), f(W)$ is the function reflecting the impact of the soil humidity on the seed biomass increment and ξ, ω, γ_4 are the parameters (Johnson and Moss, 1976; Sambo, 1977).

Results and biological applications of the model using the soybean as an example. The evaluation of model's parameters was done on the data of the soybean crops. The precision of evaluation of the parameters is not less than 95%. The response functions for some phenological phases are given in Fig. 49 for development and in Fig. 50 for growth processes. The results of the model testing are presented in Fig. 51. In tables 4 and 5 we give the values of so-called connection parameters, which means the parameters of the model that have specific physiological relevance. It is evident that the model can be used for the prediction of phenological development and yield in farm crops in various ranges of environmental conditions. However, no special attention is directed to this aspect of the problem.

This model can also be used for the purpose of theoretical research of plant ontogenesis, and gives results which will never be obtained in field experiments. We consider firstly such physiological characteristics as optimal values of environmental factors for growth and development or so-called connection parameters.

For any plant species to be able to survive, the plant requires a rhythm of growth and development processes, which could correspond to the typical trends of climate changes within particular region. To be able to receive such a rhythm, every species must acquire the proper regulators of ontogenesis which depend both on the specific features of all of its vital processes and on the environmental conditions (Chailakhyan, 1975). The most widespread and the best investigated factors are the thermal and photoperiodic regulators of flowering. The photoperiodic regulation of flowering is of a distinctly adaptive pattern. When studying this property, we discovered that this response is an ontogenetic adaptation not to day length as an individual environmental factor, but to the annual rhythm of the entire complex of favorable and unfavorable conditions within the ecological niche occupied by the particular plant species (Stepanova, 1985; Whittaker, 1975). The thermal regulation of plant development has the same general properties as the photoperiodic one (Johnson and Thornley, 1985).

On the above discussion we see that two results are essential for our work: (i) the environmental factors that are optimal for the duration of the ontogenetic stages are genetically substantiated; and (ii) these optimal values of environmental factors regularly change within the life cycle of a species. Let us consider the results from identification of the parameters of the submodel of phenological development.

The values of the optimal maximum daily air temperatures are found to increase from the moment of sowing to the interphase stages of sprouting-flower budding at temperatures 26 to 35 ^0C ; they then gradually decrease to the stage of waxy ripeness-complete ripeness, down to 19 ^0C . As to the minimum daily air temperature, such gradual variation has not been found. Unfortunately, there are no data on the maximum and minimum air temperatures that could be optimal for soybean development; however there are data from different sources presenting the average daily air temperature optimal for soybean development. In view of this, we had to calculate the average daily air temperature by the maximum and minimum values obtained in the model. Our model values proved to differ from the existing experimental ones by only 2.0-3.5 ^0C (Stepanova, 1972).

We chose 15 h as the optimal length of photoperiod for the interphase stage of sprouting-flower budding and 16 h for the stage of budding-flowering. The optimal values of soil humidity for soybean development, as obtained by the identification of the parameters, also agree with the available biological concepts. For the period of sowing-sprouting the soil humidity of 47% lowest moisture capacity (LMC) is thought to be optimal. The optimal soil humidity is found at the stage of flowering-seed filling, reaching 81% LMC. Later on, the values of optimal soil humidity gradually decrease to the lowest level of 31% LMC at the stage of waxy ripeness- complete ripeness. There is a hypothesis that if the soil humidity reaches the level of the highest moisture capacity at this stage, no ripening is possible. As the index of soil humidity decreases, the rate of development is increasing; thus, a higher soil humidity at the stage of waxy ripeness-complete ripeness prolongs the phase of development (Leopold, 1961).

We shall not deal at length with the analysis of optimal values for the environmental factors in the submodels of biomass growth and distribution of assimilates. Suffice it to mention that they completely correspond to the existing biological concepts and hypothesis, demonstrating a regular change during the ontogenesis.

Thus, the following computer simulations were done on the given model: the optimal values of environmental factors for the process of phenological development were entered into the model (Fig.52). Then the optimal values for biomass growth were entered into the model (see Table). The results of this experiment are given in Fig. 53. It can be seen that in the first case the development was as rapid as possible and gave a very small yield. In the second case we have the inverse situation. Moreover, we can identify the optimum temperature values for development (35 ^0C , Table 4) compared to the 20 ^0C corresponding value for growth (Table 5).

Thus, on the basis of computer simulation we propose that the result of having optimal values of environmental factors for the development and growth of plant species is some kind of regulatory or adaptive mechanism. In crucial environment conditions the speed of development is very high. Plants achieve ripeness very quickly without giving a high yield; however, the reproductive functions are completed. In favorable environmental conditions the plant species will grow for a very long period of time; the yield will be very high, but the vegetative period will be too long. Furthermore, we achieved one more result, which will never be obtained in the field or from the laboratory experiments: the values of minimal duration of phenological time $\bar{M}$. This is why there are only a few tentative values of experimentally investigated indices of $\bar{M}$ which we compare with our model values (Stepanova, 1985).

14. Conclusion

Work on environmental indicators is, as we have noted in this paper, carried out in many countries and international organizations.

It is useful to contrast the past and present public perception and awareness of environmental problems. In the past, most problems were related to an obvious cause, such as emissions from a particular source that was found to be offensive and damaging to the environment. The effects were easily and convincingly related to the cause. controls could be designed and the environmental responses predicted with considerable certainty.

Now , the nature of environmental degradation is different. We are faced with pollutants an effects with more subtle cause-effect relationships, often characterized by larger geographic areas of interest and longer term potential damage. The environmental damages are more chronic that the acute problems of the past.

Acid rain and climate change are good examples; they are caused by a variety of pollutants from a number of sources and damage to ecosystems occurs over many years. It is much more difficult for both the public and for the research community to understand the nature of such complicated environmental phenomena. We can no longer focus on single pollutants in a single medium (air, water, soil, etc.). Instead, we must now consider interactions among many pollutants, mixing among the various media, and potentially affecting many components of the ecosystem in both indirect and direct ways.

Relating observed damage to specific causes requires an understanding of the physical, chemical, and biological linkages that are involved. Developing objective and workable control strategies requires that the relative importance of different causes be ordered properly, so that effort is not wasted on regulating emissions that are not the most effective. Detailed, high-quality scientific information is necessary to provide a sufficient level of understanding. In essence integrated approach base on the complex environmental indicators are required. The focus of environmental indicators is on understanding and explaining changes that are detected and on providing the basis to predict future changes.

Ecological indicators as we pointed out have a very long history, however it is only in the last several decades, the concept of ecological indicators has evolved in response to the various requirements for assessment, coordination standardization, and collaboration among different environmental activities.

Predicting ecosystem impacts requires sophisticated computer simulation models that represent a synthesis of the best available understanding of the way these complex systems function. The more general objectives of human impact modeling are to predict ecosystem response as a result of various site-specific management alternatives and natural changes. Development of this capability is essential for ecosystem management and also for modeling regional an global ecosystem response to regional and global climate change, sea level rise resulting from atmospheric CO_2 enrichment, acid precipitation, toxic waste dumping, and a host of other potential impacts.

Several recent developments make this kind of modeling feasible, including the ready accessibility of extensive spatial and temporal data bases and advances in computer power and convenience that make it possible to build and run predictive models at the necessary levels of spatial and temporal resolution.

Assessing environmental health in the context of sustainable development requires systems analysis, modeling and set of environmental indicators in order to put all the individual pieces together into coherent picture.

This paper is meant as a contribution to some new environmental concepts and pointing out some of the choices that will have to be made when constructing a set of environmental indicators.

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List of Figures

Identify Values
⇓
Develop Key Assessment Questions
⇓
Identify Existing Indicators or Develop New Indicators
⇓
Consider Relevant Stressors
⇓
Develop Conceptual Models/Evaluate Existing Models
⇓
Evaluate Condition Indicators
⇓
Implement Priority Indicators and Reassess on
Periodic Basis

Table 1. Conceptual model of EMAP indicator development and implementation strategy.

TABLE 2. Main aggregation functions

Method	Equation	Equation No.
Unweighted sum	$I=\frac{1}{n}\sum_{i=1}^{n} q_i$	(1)
Weighted sum	$I=\sum_{i=1}^{n} q_i w_i$	(2)
Unweighted product	$I=(\prod_{i=1}^{n} q_i)^{1/n}$	(3)
Weighted product	$I=\prod_{i=1}^{n} q_i^{w_i}$	(4)
Minimum operator	$I=\min(q_1, q_2, \dots q_n)$	(5)
Maximum operator	$I=\max(q_1, q_2, \dots q_n)$	(6)
Solway modified unweighted sum	$I=\frac{1}{100}(\frac{1}{n}\sum_{i=1}^{n} q_i)^2$	(7)
Solway modified weighted sum	$I=\frac{1}{100}(\sum_{i=1}^{n} q_i w_i)^2$	(8)

I = environmental quality index, n = the number of parameter, q_i = environmental quality score of the parameter i and w_i= the weighting factor of the parameter i.

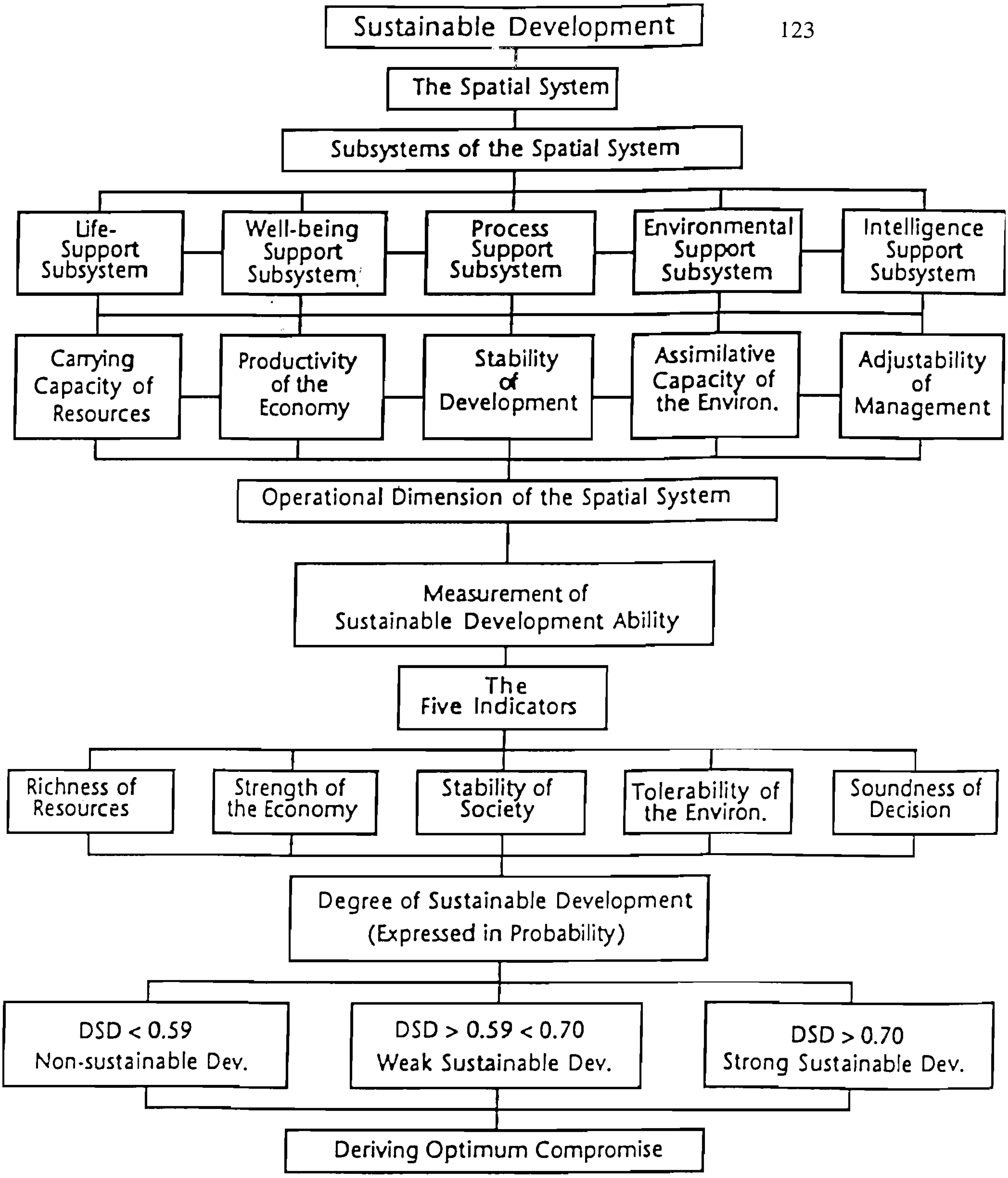


Figure 1. A spatial systems framework for evaluating sustainable development.

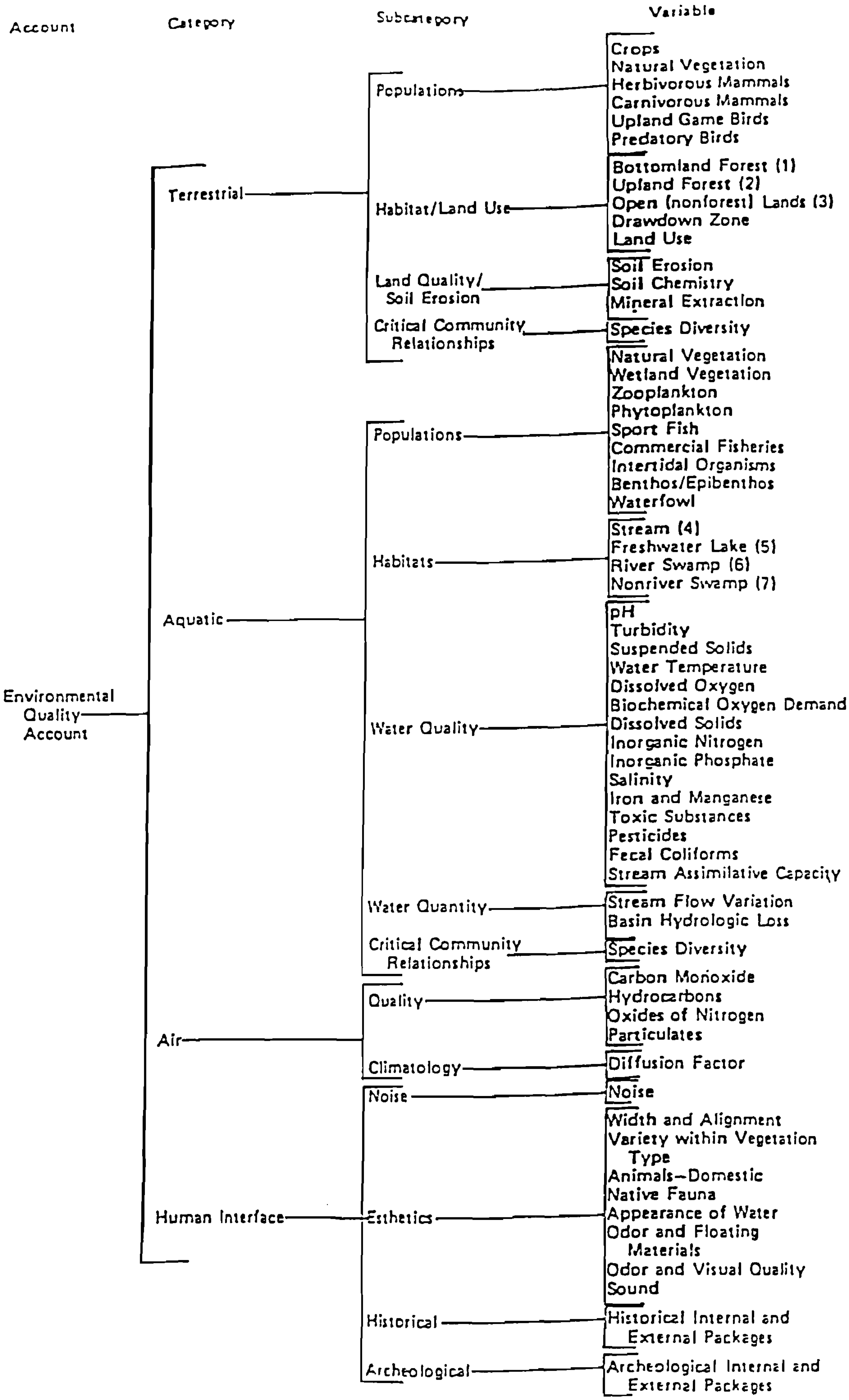


Figure 2 Structure of the Environmental Quality Account

Fig. 3

ENVIRONMENTAL QUALITY

continued

Environmental Quality Indicators (EQI)

LAND

1. People and the Land
   - A. Population
     - Population totals: growth, rate of growth
     - Spatial distribution: region, metropolitan/nonmetropolitan, coastal, residential preference
   - B. Patterns of Major Land Use
     - Specialized uses
     - Cropland/Forest/Grassland/Urban
     - Miscellaneous uses
2. Critical Areas
   - A. Wetlands
     - Extent, location
     - Condition, use
     - Protections
   - B. Wild Areas
     - Wilderness, National Wild and Scenic Rivers
     - Extent, location
   - C. Parks
     - Number and area, location, type
     - Condition, use
   - D. Historic Properties
     - Number, type
   - E. Risk Zones: Floods, Hurricanes, Windstorms, Earthquakes
     - Location, population exposed
     - Damage
3. Housing and Neighborhoods
   - A. Stock and Flow of Housing
     - Type, age, and size of housing
   - B. Condition and Quality of Housing
     - Housing unit condition: standard units, living space, facilities, and appliances
     - House and neighborhood quality conditions: overall opinion, neighborhood deficiencies, and access to neighborhood services
   - C. Impacts on Natural Environment
     - Land used
     - Energy and materials used
4. Industrial Growth and Wastes
   - A. Industrial Establishments
     - Location of industry by region, metro/nonmetro, coastal areas
     - Critical lands used in industrial and commercial development
   - B. Wastes
     - Generation and disposal: emissions to air, water, other
     - Recycling
5. Hazardous Substances, Radiation, and Noise
   - A. Hazardous Substances
     - Sources, types, levels of production and use
     - Prevalence, residuals
     - Effects: workers by selected occupations
     - Control
   - B. Radiation
     - Sources, effects
     - Contamination
   - C. Noise
     - Levels, sources
     - Exposure, effects
6. Transportation
   - A. The Transportation System
     - Stock and flow of transportation right-of-ways: roadways, railroad, pipelines, electric lines, waterways, airways
     - Stock and flow of vehicles: automobiles, trains, airplanes, boats, trucks, buses
   - B. Use of the System
     - Movement of goods: mode-split
     - Movement of people: mode-split, commuting
   - C. Impacts on the Natural Environment
     - Energy used: energy requirements, automobile efficiency
     - Air pollution
     - Noise: motor vehicles, aircraft
7. Energy and Minerals
   - A. Energy
     - Overview of production and consumption: U.S. and world, imports and exports
     - Supply: fossil fuels (oil, natural gas, coal, uranium), other
     - Consumption: energy flows, generation of electricity
     - Use and conservation by sector: household, industrial, transportation
   - B. Minerals
     - Production and consumption: iron and nonferrous metals, imports and exports, materials substitution
     - Reserves and resources
     - Mining, refining, and upgrading: impacts on the natural environment
     - Recycling
8. Natural Resources: Living Resources
   - A. Cropland
     - Location, types
     - Productivity: crops, livestock
     - Agricultural inputs

continued

Quality: soil erosion
Agricultural impacts on the natural environment: water pollution, energy use in the food system
B. Forests
Location: region, biome
Ownership: commercial, other
Quality/Productivity: species composition, age/size of growing stock
Management: harvesting practices
Use and consumption: timber, natural habitat, recreation
C. Grazelands
Accessibility: location and ownership
Quality: condition of the resource, productivity
9. Wildlife
A. Abundance/Distribution
Big game and water fowl
B. Wildlife Condition
Threats to wildlife
Land use
Toxic substances
C. Wildlife Management
Habitant management
Endangered and threatened species
Resource competition

WATER
10. Water Quality
A. Ambient Conditions
Levels of major pollutants in streams
Violations of standards
B. Discharges
Point and nonpoint source runoff
C. Effects/Impacts
Beaches, recreational areas
Wildlife
Other
D. Control/Treatment
Municipal waste treatment
Other
E. Public Water Supplies
Condition of drinking water
F. Lakes
Eutrophication
G. Oceans
Oceandumping
Oil spills
11. Water Resources
A. Abundance/Distribution
Surface water
Ground water
Precipitation

continued

Drought
B. Withdrawal and Consumption
Supply and demand
Withdrawal and use by sector
C. Environmental Impacts of Current and Projected Use

AIR
12. Air Quality and the Atmosphere
A. Ambient Conditions
Air Pollution Index: selected cities
Criteria pollutants: concentration and frequency of occurrence in representative Air Quality Control Regions
Non-Criteria pollutants
B. Effects
Health: population exposure, morbidity, mortality
Economic
Natural environment
C. Emissions
Sources
Controlled and uncontrolled emissions
D. Climate
Temperature trends
Wind and windstorms
Rainfall and drought
E. The Stratosphere
Fluorocarbons and the ozone layer

THE BIOSPHERE
13. World Trends
A. Population
Numbers
Growth
Distribution
B. Food Production and Fish Catch
C. Energy and Materials Consumption
D. Hazardous Substances
E. Extinct and Endangered Species
F. Oceanic Shifts
Selected elements
G. Atmospheric Shifts
CO$_2$

Indicator variables for inventorying, monitoring, and assessing terrestrial biodiversity at four levels of organization, including compositional, structural, and functional components: includes a sampling of inventory and monitoring tools and techniques Fig. 4

Level in hierarchy	*Classes of indicators*			
	Composition	*Structure*	*Function*	*Inventorying and monitoring tools*
Regional landscape	Identify, distribution richness and proportions of patch (habitat) types and multipatch landscape types; collective patterns of species distributions (richness, endemism)	Heterogeneity; connectivity; spatial linkage; patchiness; porosity; contrast, grain size; fragmentation; configuration; juxtaposition; patch size frequency distribution; perimeter-area ratio; pattern of habitat layer distribution	Disturbance processes (areal extent, frequency or return interval, rotation period, predictability, intensity, severity, seasonality); nutrient cycling rates; energy flow rates; patch persistence and turnover rates; rates of erosion and geomorphic and hydrologic processes; human land-use trends	Areal photographs (satellite and conventional aircraft) and other remote sensing data; Geographic Information Systems (GIS) technology; time series analyses; spatial statistics; mathematical indices (of pattern, heterogeneity, connectivity, layering, diversity, edge, morphology, autocorrelation, fractal dimension)
Community ecosystem	Identity, relative abundance, frequency, richness, evenness, and diversity of species and guilds; proportions of endemic, exotic, threatened and endangered species; dominance-diversity curves; life-form proportions; similarity coefficiency; C_4–C_3 plant species ratios	Substrate and soil variables; slope and aspect; vegetation biomass and physiognomy; foliage density and layering; horizontal patchiness; canopy openness and gap proportions; abundance, density and distribution of key physical features (e.g., cliffs, outcrops, sinks) and structural elements (sngas, down logs); water and resource (e.g., mast availability; snow cover	Biomass and resource productivity; herbivory, parasitism, and predation rates; colonization and local extinction rates; patch dynamics (fine-scale disturbance processses), nutrient cycling rates; human intrusion rates and intensities	Aerial photographs and other remote sensing data; ground-level photo stations; time series analysis; physical habitat measures and resource inventories; habitat suitability indices (HSI, multispecies); observations, censuses and inventories, captures, and other sampling methodologies; mathematical indices (e.g., of diversity, heterogeneity, layering dispersion, biotic integrity)
Population species	Absolute or relative abundance; frequency; importance or cover values; biomass, density	Dispersion (microdistribution); range (macrodistribution); population structure (sex ratio, age ratio); habitat variables (see community-ecosystem structure, above); within-individual morphological variability	Demographic processes (fertility, recruitment rate, survivorship, mortality); metapopulation dynamics; population genetics (see below); population fluctuations; physiology; life history; phenology; growth rate (of individuals); accumulation; adaptation	Censuses (observations, counts, captures, signs, radio-tracking); remote sensing; habitat suitability index (HSI); species-habitat modelling; population viability analysis
Genetic	Allelic diversity; presence or particular rare alleles, deleterious recessives, or karyotypic variants	Census and effective population size; heterozygosity; chromosomal or phenotypic polymorphism; generation overlap heritability	Inbreeding depression; outbreeding rate; rate of genetic drift; gene flow; mutation rate; selection intensity	Electrophoresis; karyotypic analysis; DNA sequencing; offspring-parent regression; sib analysis; morphological analysis

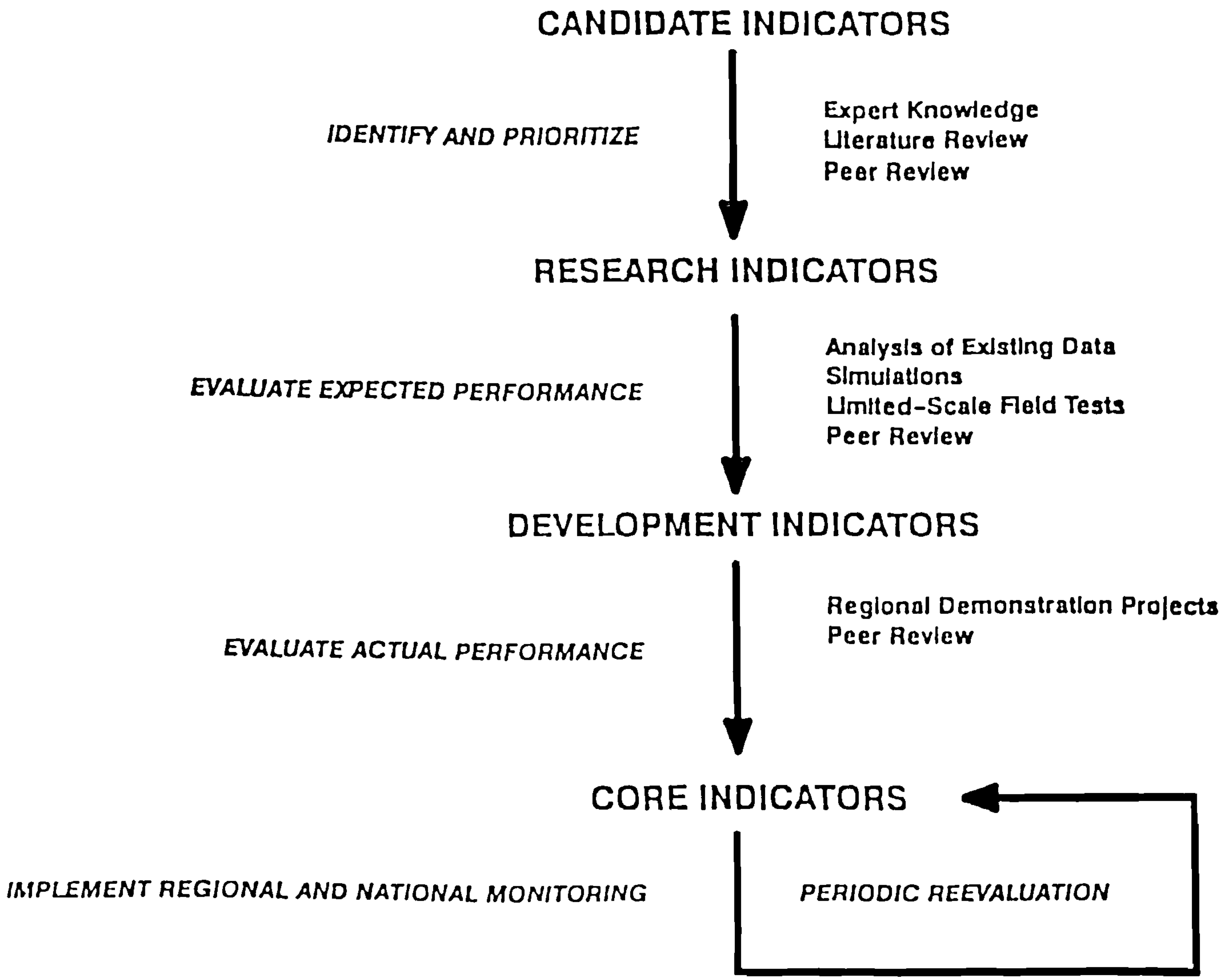
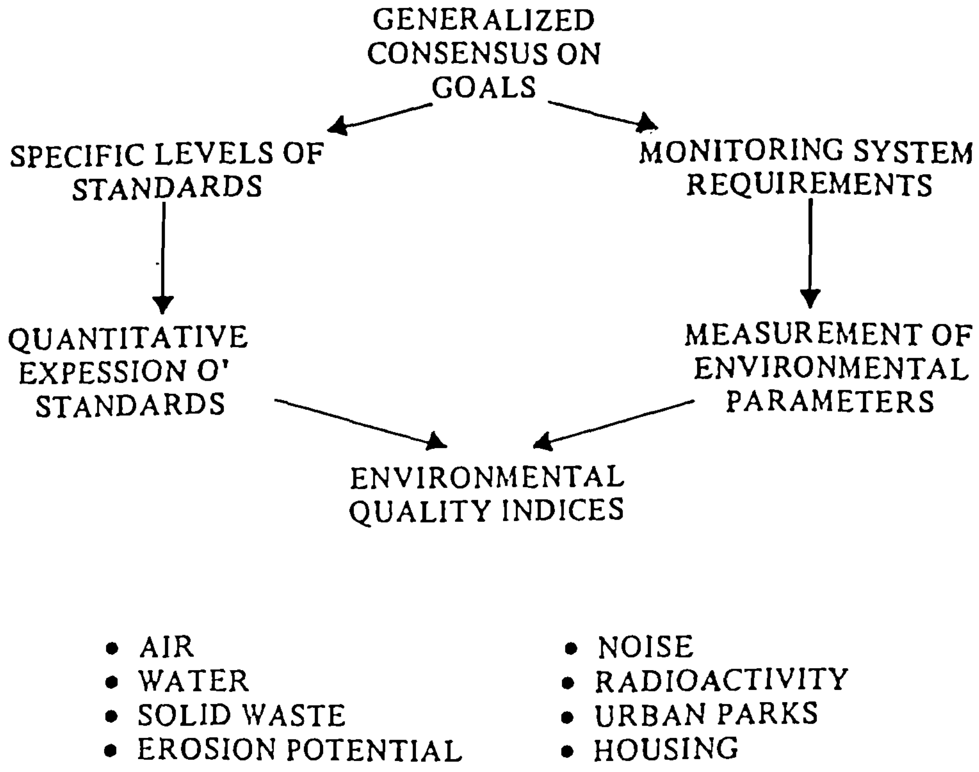
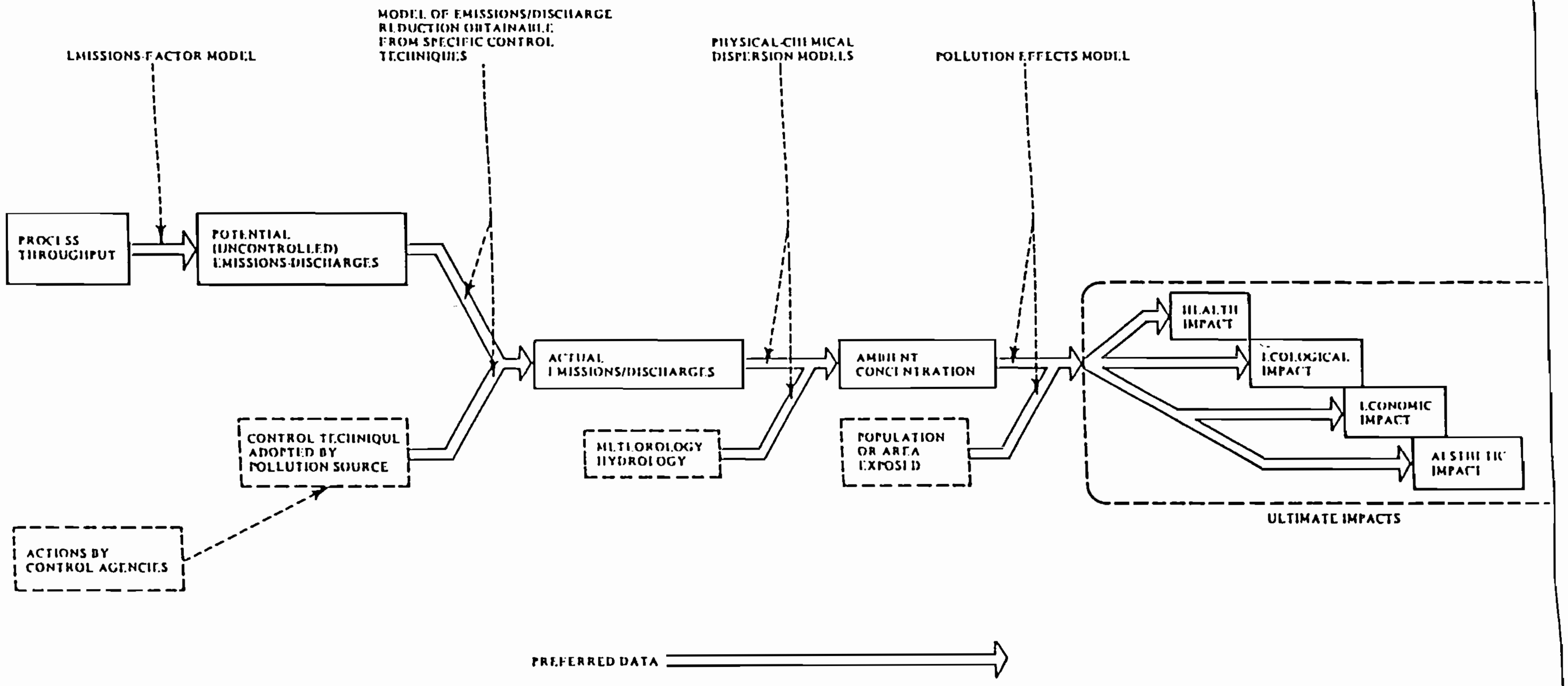


Fig. 5 Indicator selection, prioritization, and evaluation approach for EMAP (Hunsaker and Carpenter, 1990).



Source: Bisselle, C. A. *et al.*: *Monitoring the Environment of the Nation:* Report to the Council on Environmental Quality. McLean, Virginia. The MITRE Corporation, April 1971.

Fig. 6 Development of environmental quality indices.



Source: *First Report of the Environmental Measures Project: Analysis and Applications of Environmental Quality Indicators*, EPA, July 1975.

Data in the box to the right (ultimate impact data) are the most desirable for determining the real benefits of pollution control activities.

Data blocks to the left are successively further removed from ultimate impacts and are correspondingly less desirable.

Fig. 7 A ranking of environmental data for use as indicators.

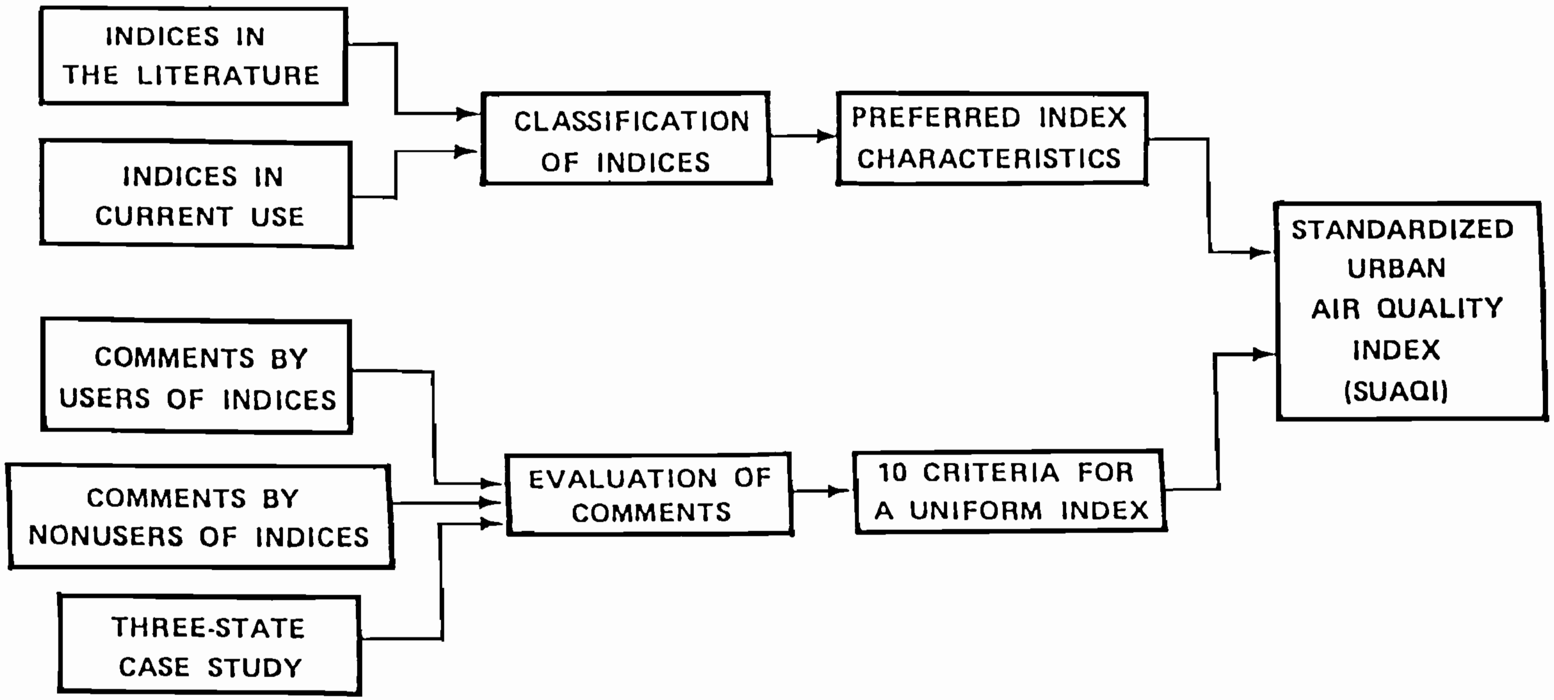


Figure 8 Development process of the Standardized Urban Air Quality Index (SUAQI).

STRUCTURE OF ENVIRONMENTAL INDICES

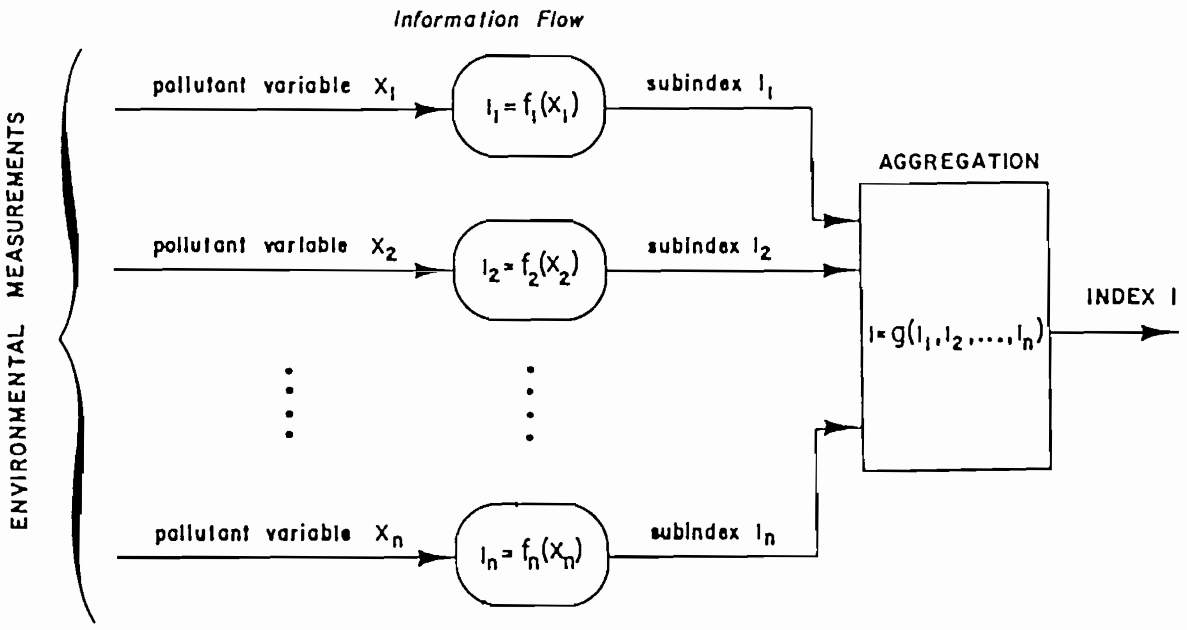
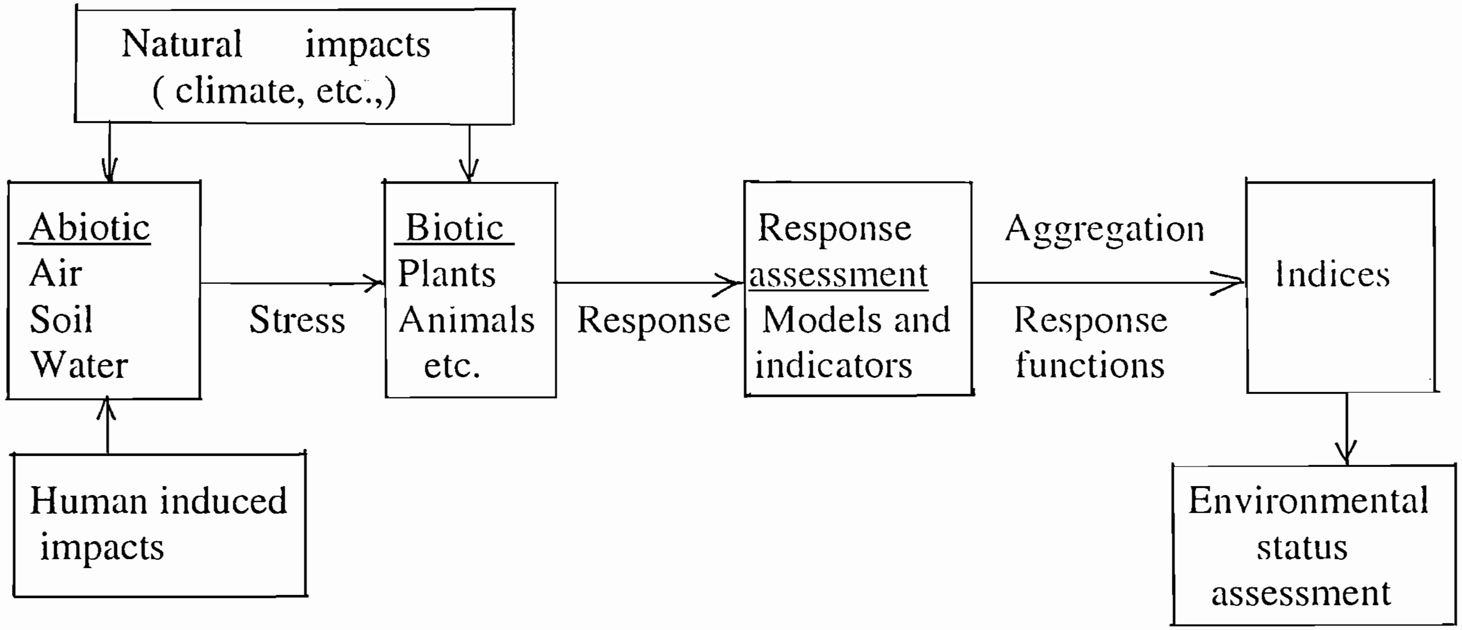


Figure 9 Information flow process in an environmental index.

Fig. 10 Definitions of some important variables (adapted and expanded from Pimm, 1984)

Variable	*Definition*
Stability	
Homeostasis	Maintenance of a steady state in living organisms by the use of feedback control processes
Stable	A system is stable if and only if the variables all return to the initial equilibrium following their being perturbed from it. A system is locally stable if this return applies to small perturbations, and globally stable if it applies to all possible perturbations
Sustainable	A system that can maintain its structure and function indefinitely. All nonsuccessional (i.e., climax) ecosystems are sustainable, but they may not be stable. To be able to sustain a system is a policy goal for economic systems
Resilience	How fast the variables return towards their equilibrium following a perturbation. Not defined for unstable systems
Resistance	The degree to which a variable is changed, following a perturbation
Variability	The variance of population densities over time, or allied measures such as the standard deviation or coefficient of variation (sd/mean)
Complexity	
Species richness	The number of species in a system
Connectance	The number of actual interspecific interactions divided by the possible interspecific interactions
Interaction strength	The mean magnitude of interspecific interaction: the size of the effect of one species' density on the growth rate of another species
Evenness	The variance of the species abundance distribution
Diversity indices	Measures that combine evenness and richness with a particular weighting for each. One important member of this family is the information theoretic index, H
Ascendency	An information theoretic measure that combines the average mutual information (a measure of connectedness) and the total throughout of the system as a scaling factor
Other variables	
Perturbation	A change to a system's inputs or environment beyond the normal range of variation
Stress	A perturbation with a negative effect on a system
Subsidy	A perturbation with a positive effect on a system

Fig. 11. Formation of environmental indices and assessment



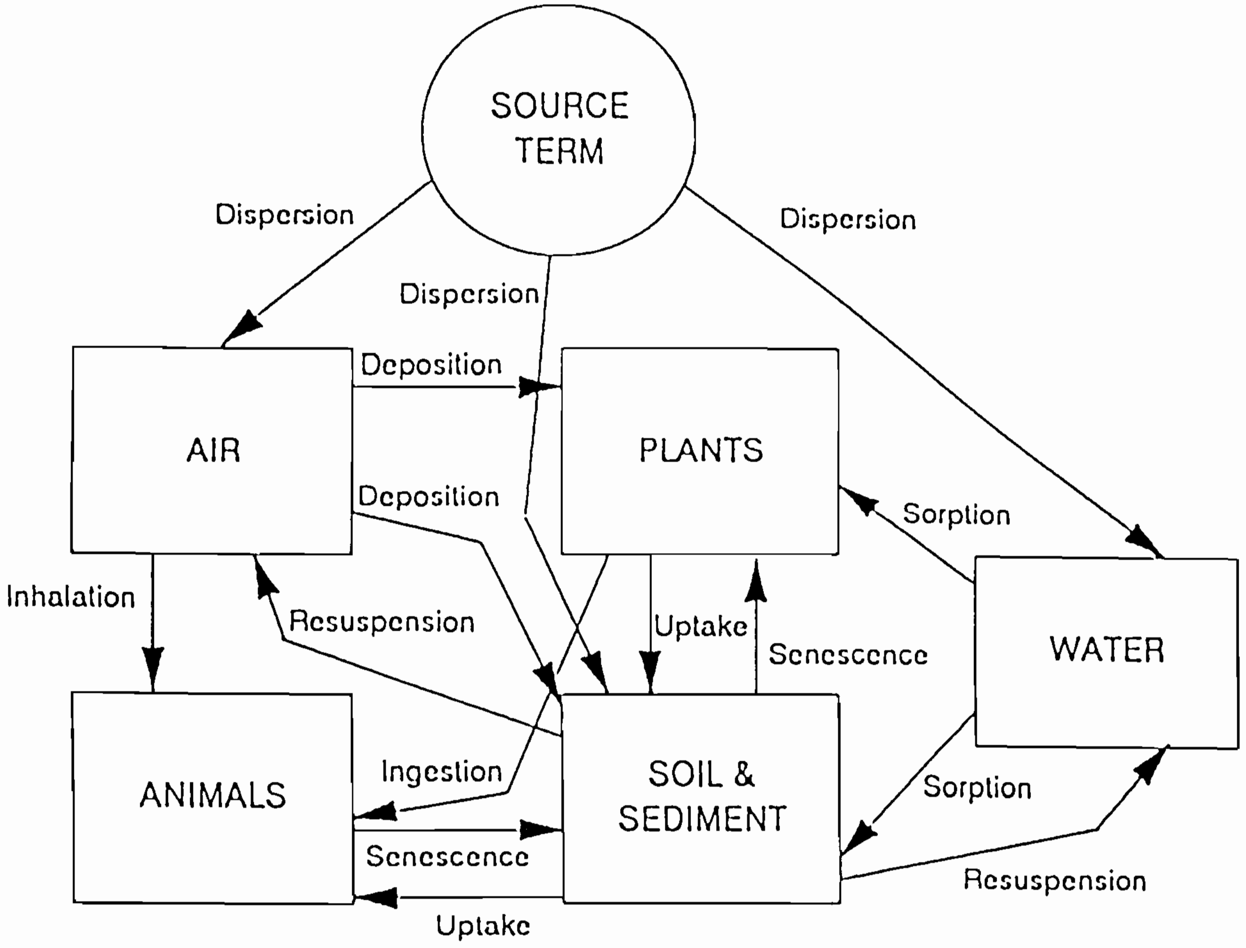


Fig. 12 Radionuclide movement through the environment.

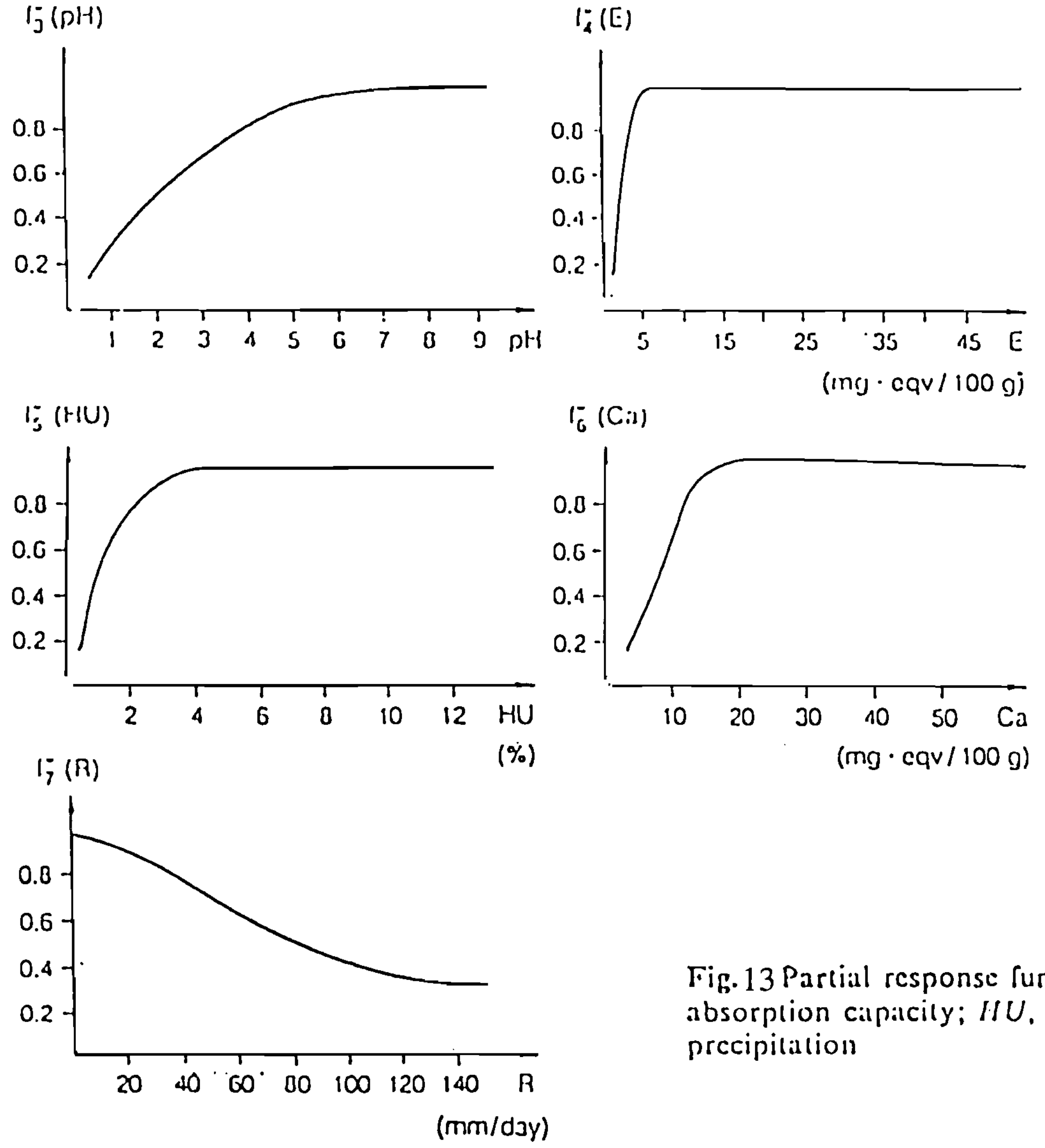


Fig. 13 Partial response functions of vegetation resistance index for spring wheat. *E*, Soil absorption capacity; *HU*, soil humus content; Ca, soil calcium ion content; *R*, daily precipitation

Fig. 14 The test.results of the vegetative block model for spring wheat in the data from Arkhipov et al. (1975)

No.	Zone	Soil types	^{90}Sr content in the yield of spring wheat: nCi/kg (dry wt.) mCi/m^2 (soil)			
			Grains		Stems	
			Field data	Model	Field data	Model
1	Middle taiga	Podzolic	9.7	9.68	18.0	17.9
2	Southern taiga	Sod-podzolic	0.95	0.78	3.6	3.3
3	Forest-steppe	Chernozems	0.54	0.43	1.6	1.3
4	Steppe	Leached chernozems, grey ~ forest soils	0.43	0.41	1.4	1.3
5	Subtropical semi-desert[a]	Serozems	0.94	0.70	4.3	3.2
6	Desert[a]	Burosems	1.9	0.6	11.0	2.7

[a] With irrigation

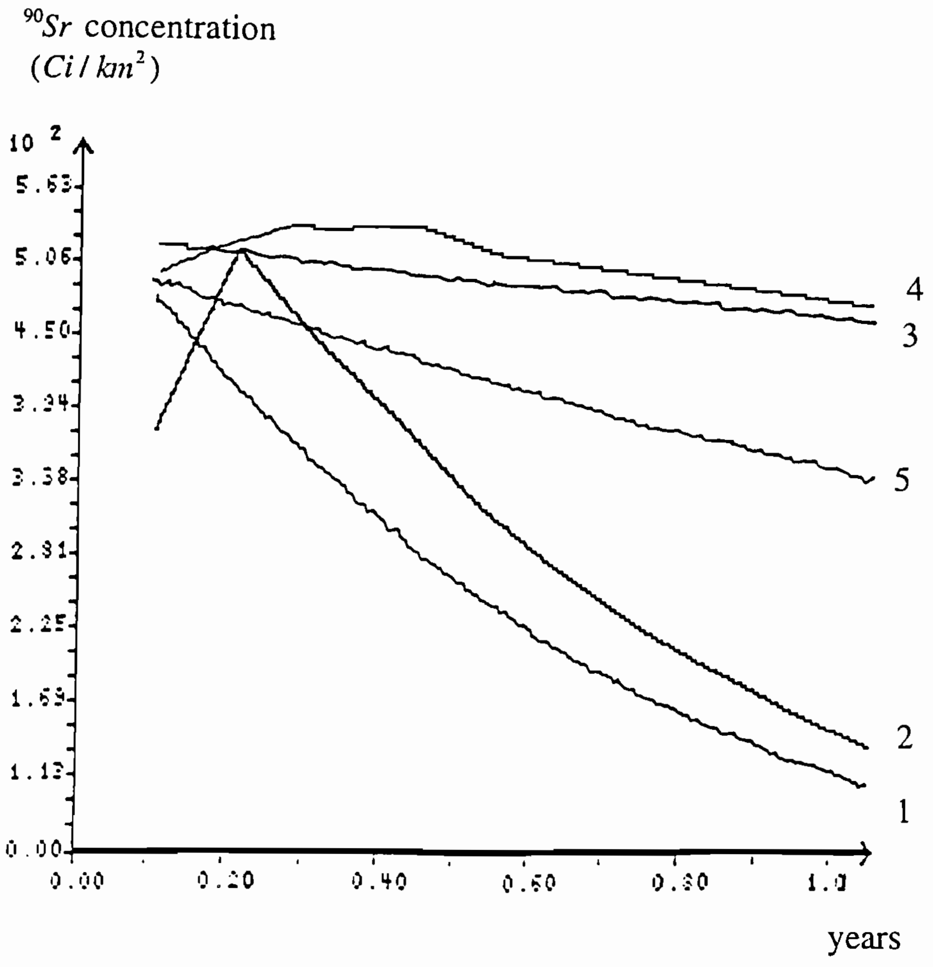


Fig 15. ^{90}Sr dynamics in soils of various ecosystems:

1. middle taiga, winter contamination;
2. middle taiga, summer contamination;
3. forest-steppe, winter contamination;
4. forest steppe, summer contamination;
5. subtropical, winter contamination.

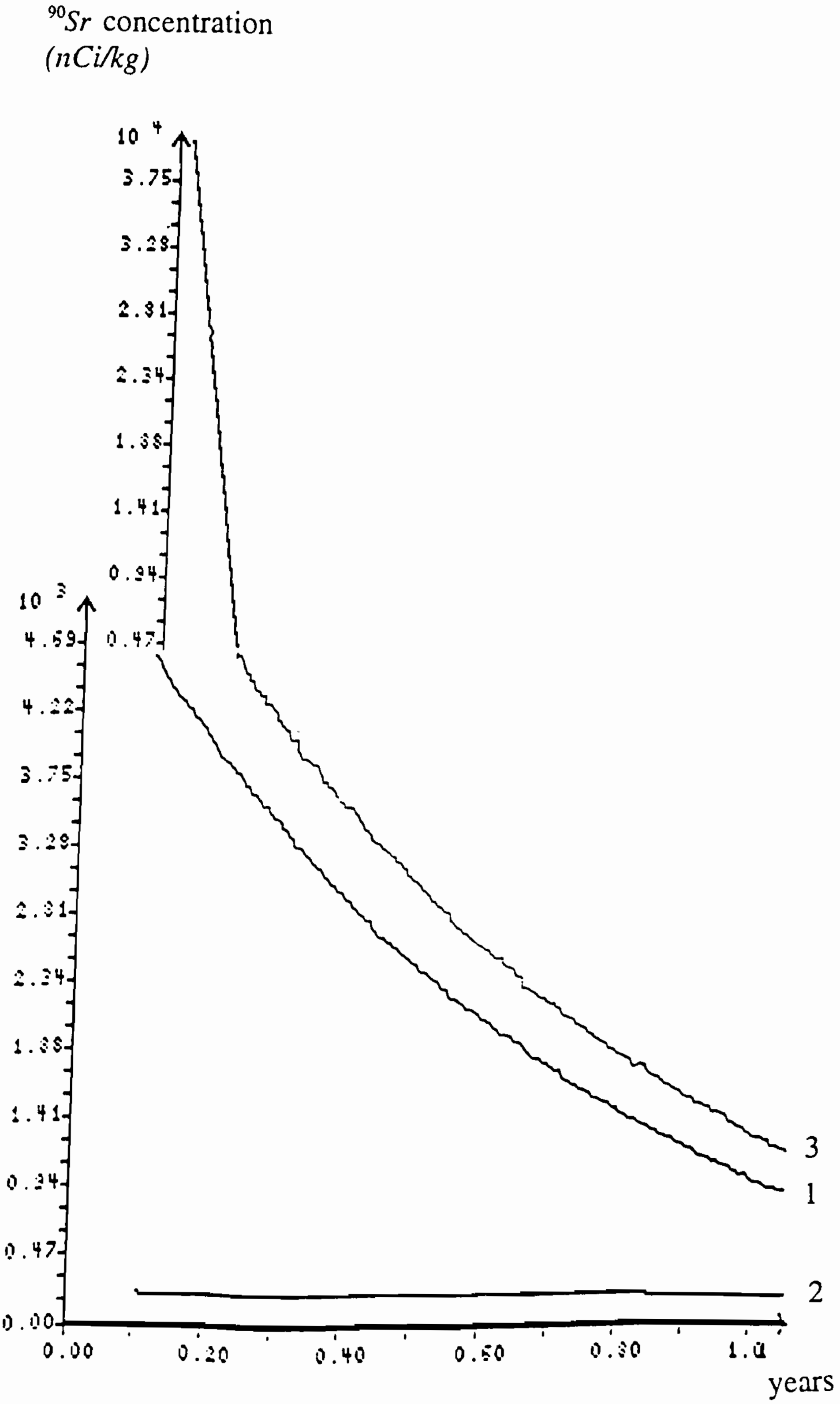


Fig. 16. ^{90}Sr dynamics in vegetation (spring wheat) in varous ecosystems:

1. middle taiga, winter contamination;
2. forest steppe, winter contamination;
3. middle taiga, summer contamination.

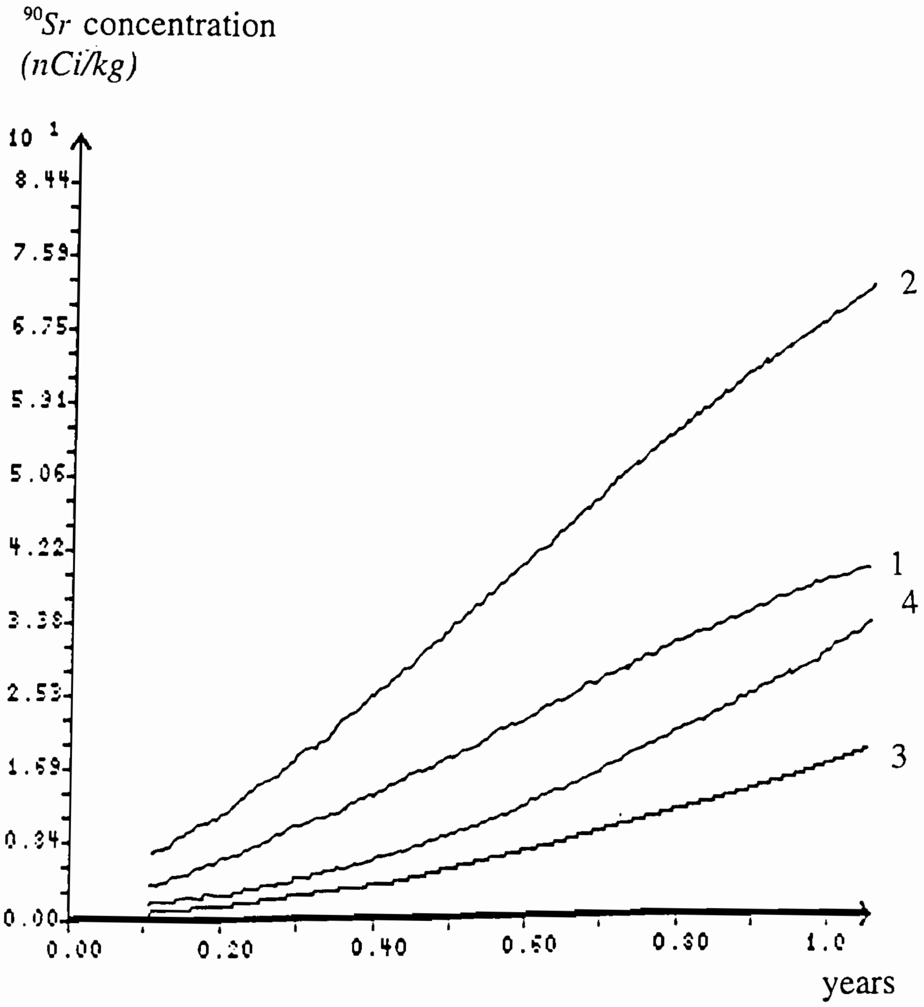


Fig. 17. ^{90}Sr concentration in hydrobionts in the lakes of various ecosystems:

1. middle taiga, silt sediments;
2. middle taiga, sand sediments;
3. forest steppe, silt sediments;
4. forest steppe, sand sediments.

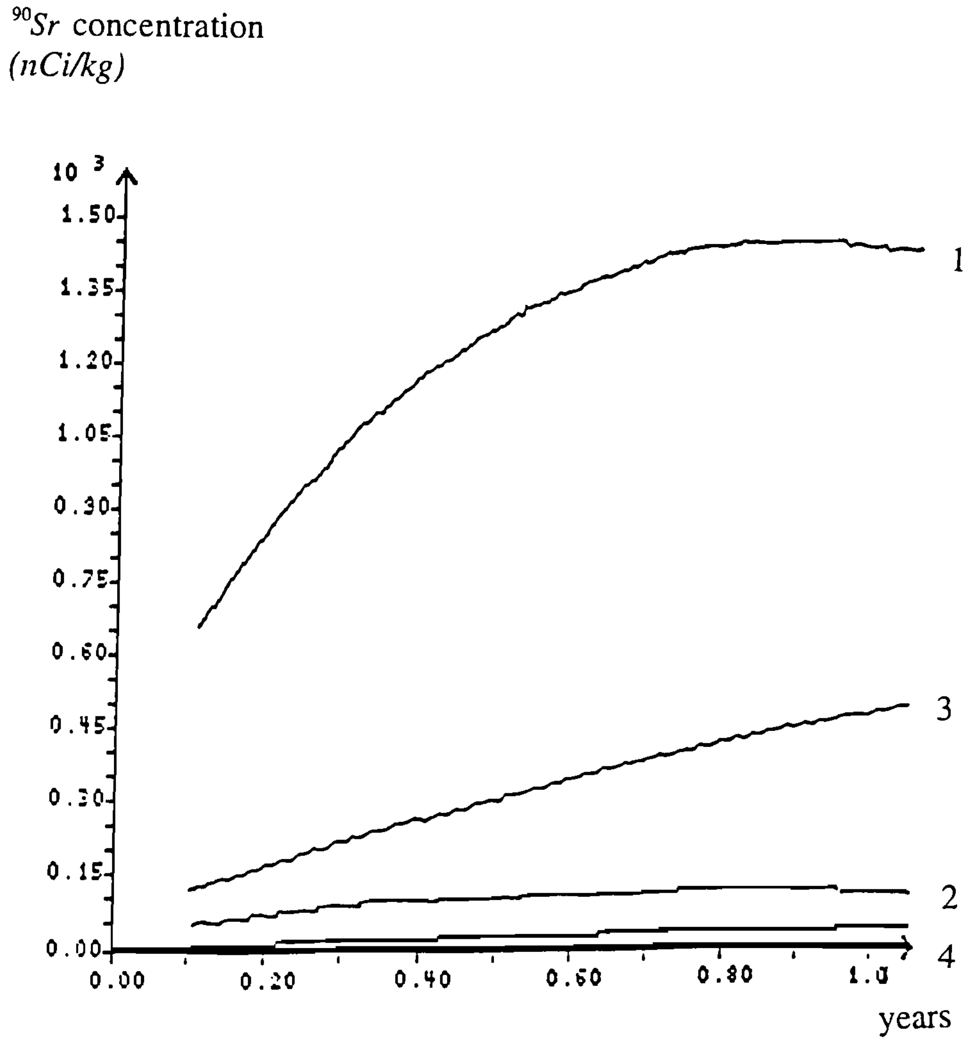
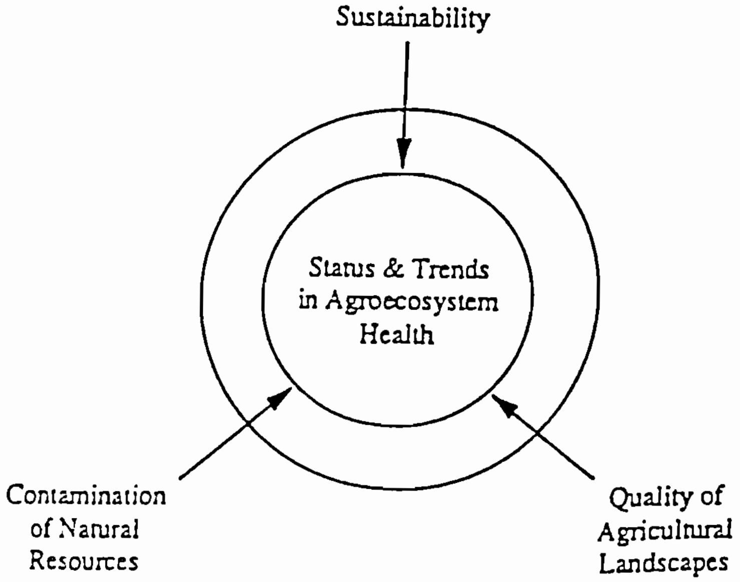


Fig. 18. ^{90}Sr concentration in floor deposits of different types in the lakes of various ecosystems:

1. middle taiga, silt sediments;
2. middle taiga, sand sediments;
3. forest steppe, silt sediments;
4. forest steppe, sand sediments.



Indicators of the ecological status

Fig. 19 Assessment endpoints that will be addressed with a suite of indicators to determine the status and trends in agroecosystem health.

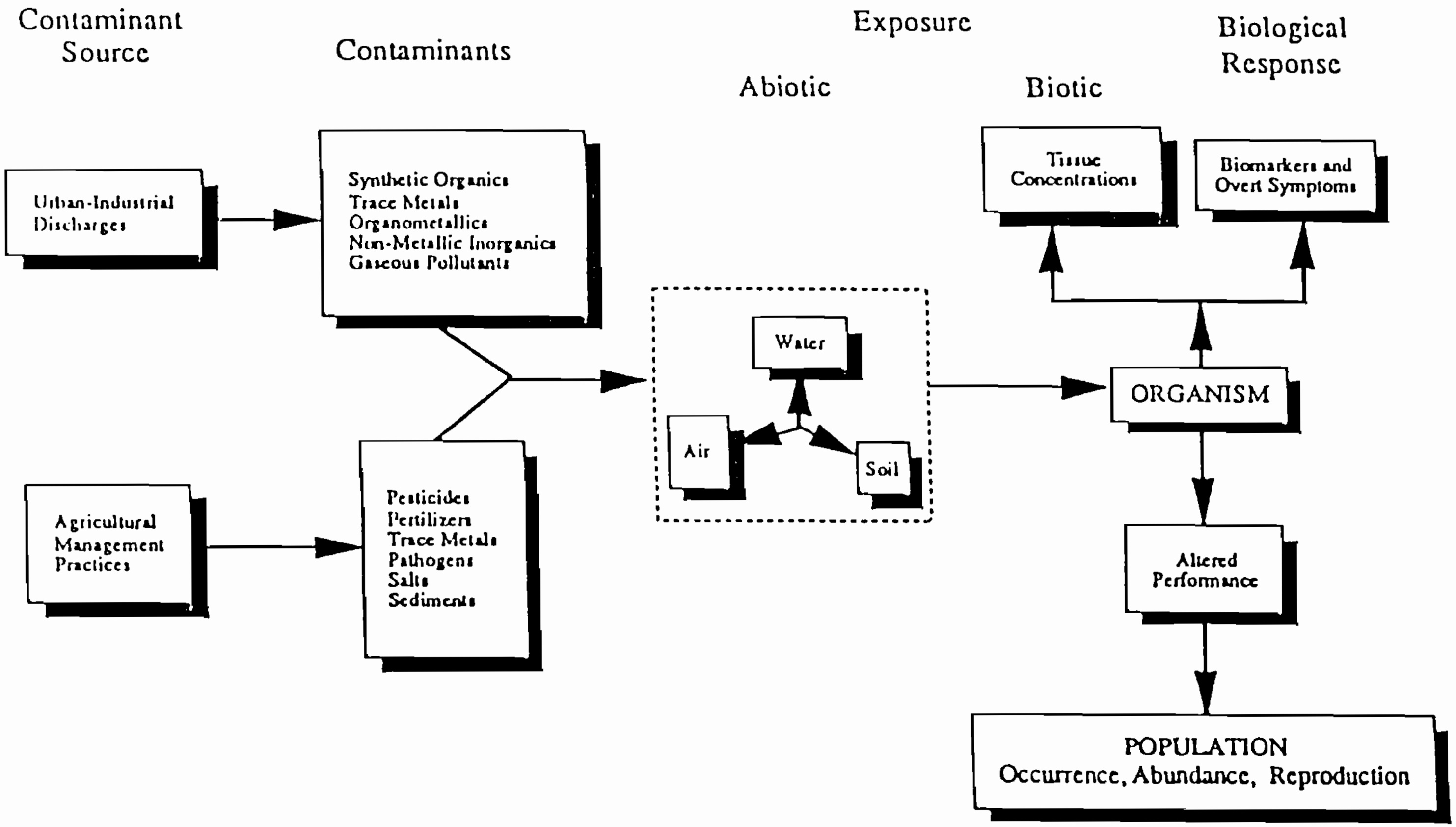


Fig. 20 Development of indicators to assess the contamination of natural resources.

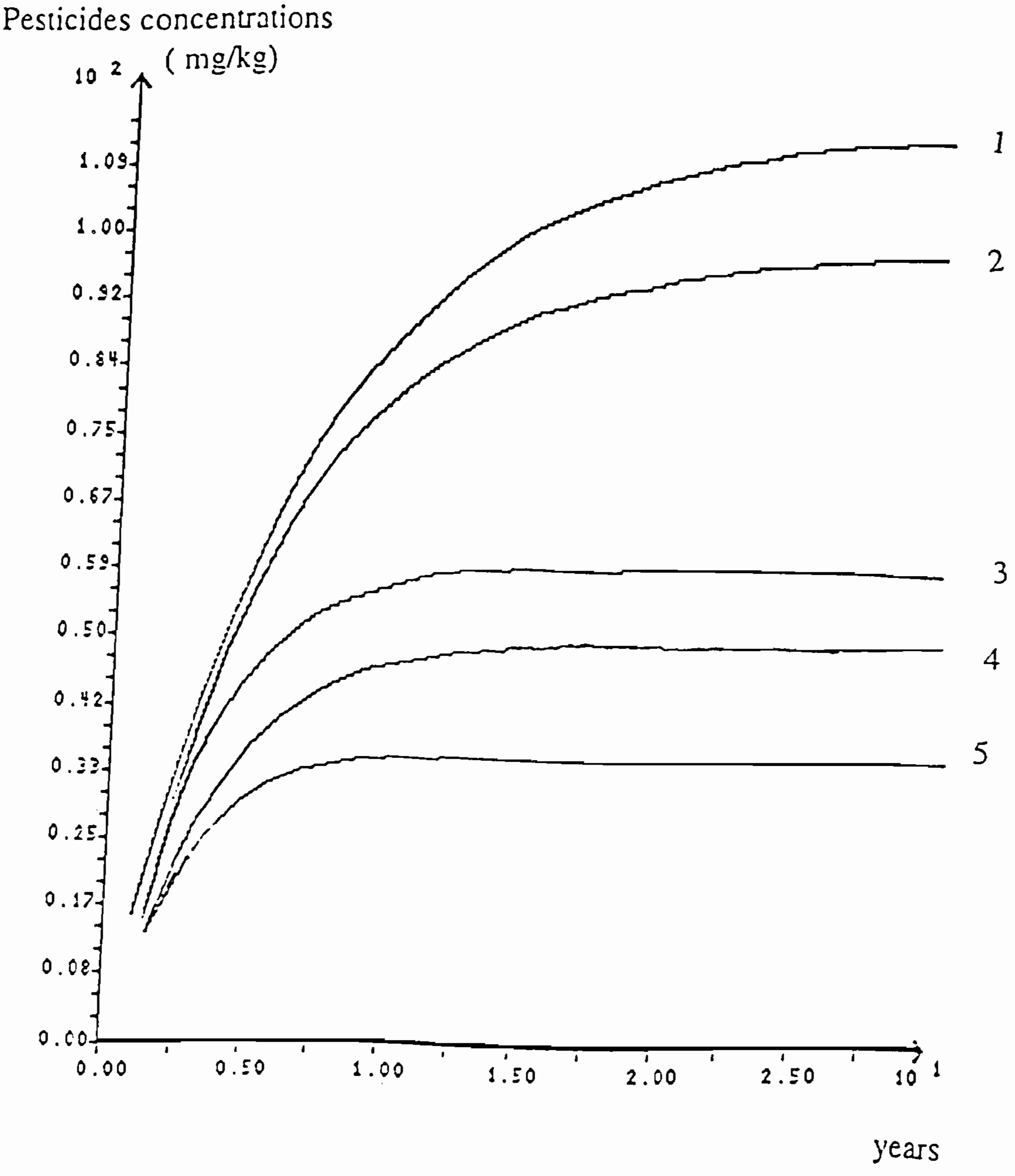


Fig. 21 The results of simulation experiments. Pesticides dynamics in soils of various ecosystems:

1 - middle taiga;

2 - southern taiga;

3 - forest steppe;

4 - steppe;

5 - subtropical.

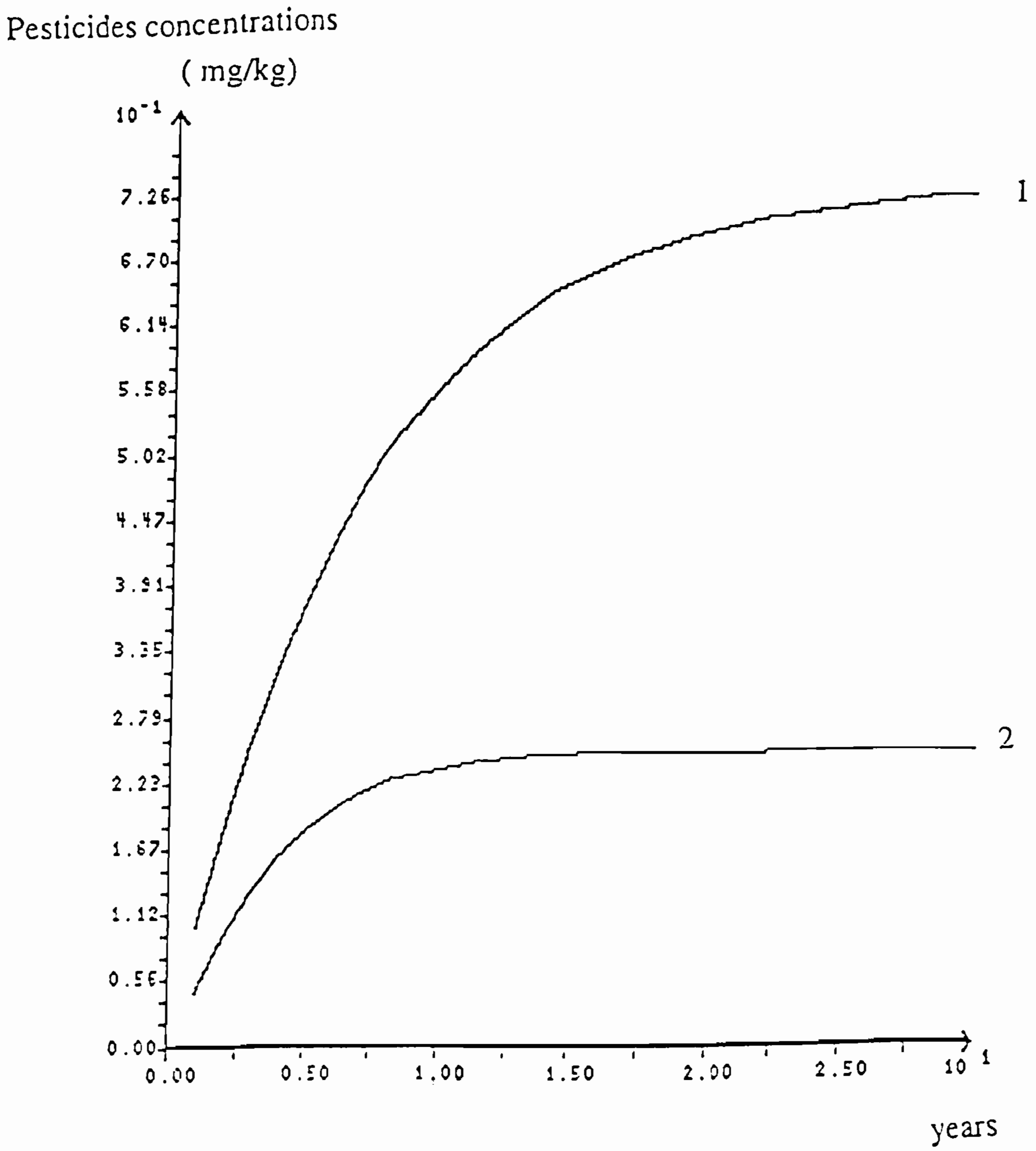


Fig. 22 The results of simulation experiments. Pesticides dynamics in vegetation (potato) in various ecosystems:

1 - middle taiga;

2 - forest steppe.

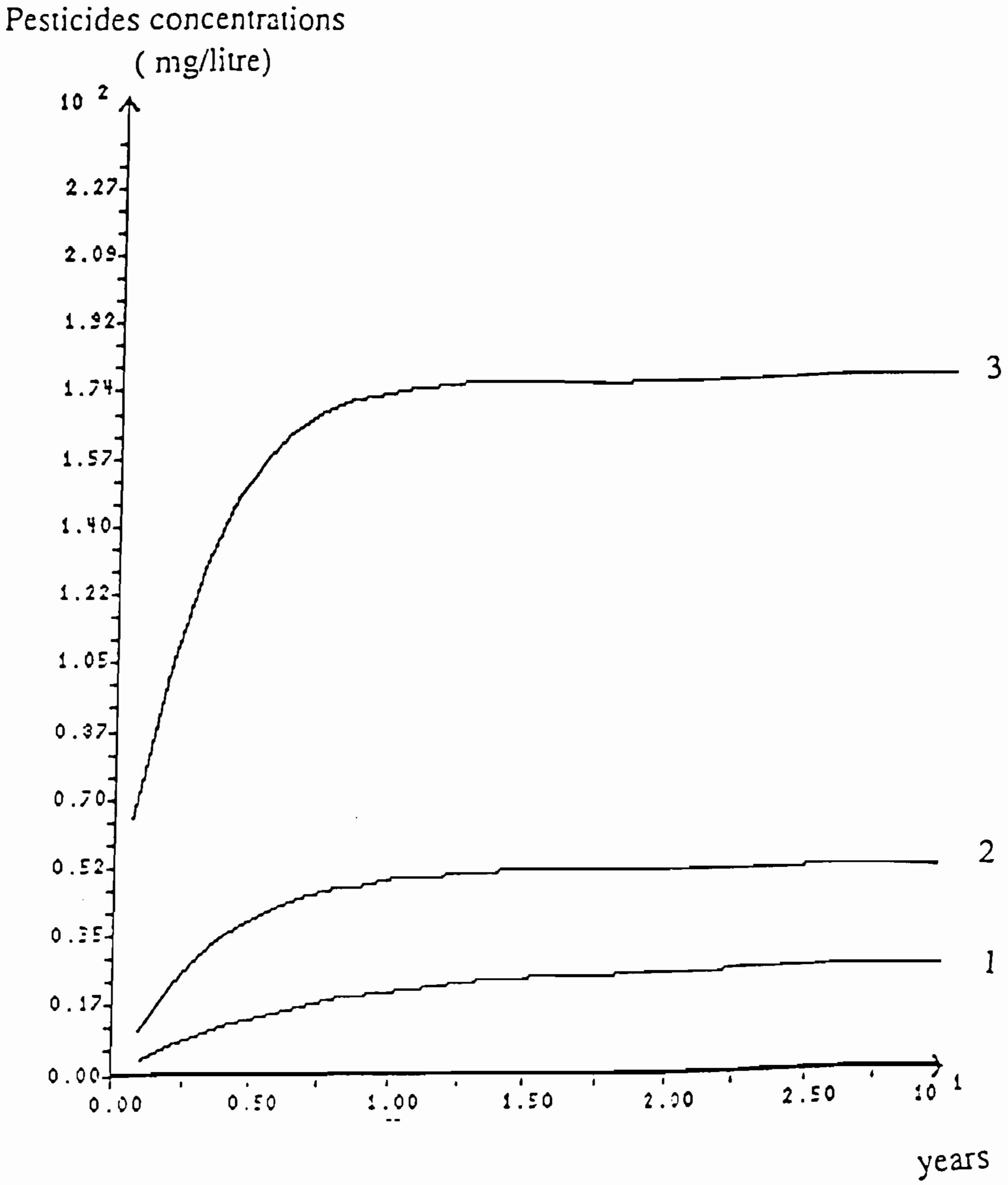


Fig. 23 The results of simulation experiments.
Pesticides dynamics in surface water
in various ecosystems:
1 - middle taiga;
2 - forest steppe;
3 - desert.

Fig. 24 Definitions of sustainability

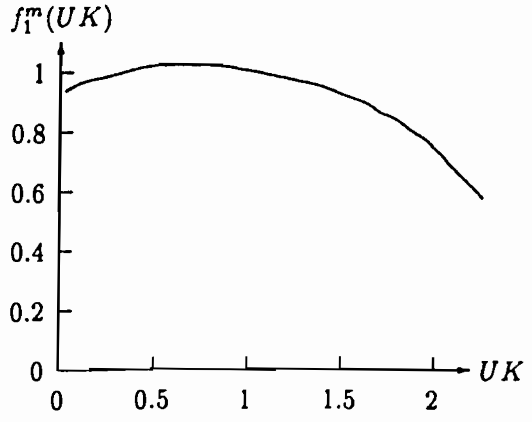
WCED, 1987	Sustainable development is that which 'meets the needs and aspirations of the present without compromising the ability of future generations to meet their own needs'.
FAO, 1989	Sustainable agriculture involves the successful management of resources for agriculture to satisfy human needs, while maintaining or enhancing the quality of the environment and conserving natural resources.
Keaney, 1989	Agricultural systems that are environmentally sound, profitable and productive and that maintain the social fabric of the rural community.
Okigbo, 1991	A sustainable agricultural production system is defined as one which maintains an acceptable and increasing level of productivity, that satisfies prevailing needs and is continuously adapted to meet the future needs for increasing the carrying capacity of the resource base and other worthwhile human needs.
Young, 1989	Sustainable land use is that which achieves production combined with conservation of the resource base on which that production depends, thereby permitting the maintenance of productivity.
Conway, 1985	Productivity can be defined as the increment in valued product per unit time and is best measured as yield or income per unit of land per time. Stability is the degree to which productivity is free from the variability caused by normal fluctuations in environmental variables, such as climate; it is most conveniently measured by the reciprocal of the coefficient of variation in yield or net income. Sustainability can be defined as the ability of a system to maintain productivity in spite of larger disturbances such as repeated stress or a major perturbation (for example, the building of soil salinity or a sudden outbreak of a new pest or disease).
Spencer and Swift, 1992	A sustainable cropping system is one in which the output trend is non-declining and resistant, in terms of yield stability, to normal fluctuations of stress and disturbance.

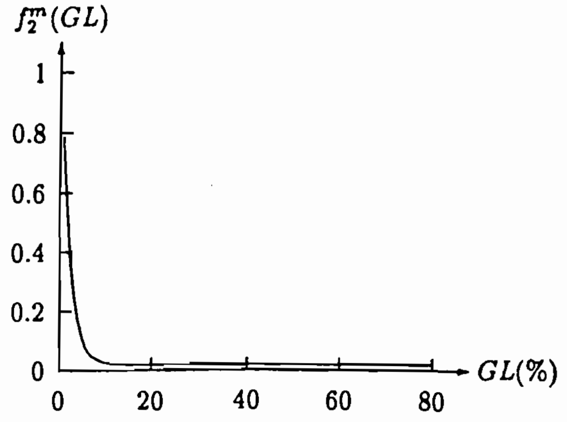
Table 3.

Validation of submodel of humus formation in the natural ecosystems

Number and soil type	Humus content				KHUM	KMIN	KHUM/KMIN
	tons/hectare		%				
	1*	2**	1*	2**	1*	1*	1*
1. Tundra soils	82.5	90.0	3.23	3.23	0.139	0.0016	84.9
2. Illuvial humic podzols	93.8	110.0	2.84	3.61	0.182	0.0021	85.4
3. Podzolic soils,podzols	97.8	110.0	0.85	0.80	0.184	0.0020	89.9
4. Sod-podzolic soils	236.0	200.0	2.53	3.23	0.186	0.0024	76.0
5. Grayish-brown forest soils	455.7	400.0	2.43	5.50	0.173	0.0034	51.0
6. Light gray forest soils	322.2	300.0	2.21	2.50	0.187	0.0040	46.6
7. Gray forest soils	374.9	350.0	2.73	3.50	0.192	0.0037	52.3
8. Dark gray forest soils	380.9	400.0	3.58	5.50	0.204	0.0041	50.2
9. Leached chernozems	556.6	550.0	9.13	8.00	0.217	0.0065	38.4
10. Typical chernozems	877.2	800.0	8.56	9.00	0.225	0.0062	36.0
11. Ordinary chernozems	477.2	550.0	9.15	8.00	0.223	0.0058	38.5
12. Southern chernozems	280.3	250.0	5.62	5.20	0.176	0.0074	23.6
13. Meadow chernozems	672.8	689.0	7.10	8.00	0.206	0.0110	18.7
14. Dark chestnut soils	219.6	250.0	4.01	4.20	0.182	0.0086	21.1
15. Chestnut soils	231.9	250.0	3.22	2.80	0.140	0.0082	17.0
16. Light chestnut soils	136.9	100.0	2.85	2.00	0.132	0.0088	15.0
17. Brown semidesert soils	80.0	100.0	1.51	1.20	0.123	0.0077	15.9
18.Greyish-brown semidesert soils	44.7	50.0	1.11	0.60	0.141	0.0090	15.6
19. Serozems	60.1	50.0	1.31	0.80	0.134	0.0097	13.7
20. Leached brown soils	358.0	300.0	7.38	7.00	0.197	0.0051	38.3
21. Typical brown soils	547.5	500.0	9.80	9.50	0.203	0.0039	51.6
22.Brown carbonate soils	260.0	200.0	5.43	4.00	0.177	0.0046	38.1
23. Yellow soils	337.2	250.0	3.82	4.00	0.162	0.0054	29.8
24. Red soils	338.0	250.0	2.56	4.00	0.151	0.0076	19.9
25. Solonetz soils	202.9	150.0	2.52	2.00	0.140	0.0018	75.7

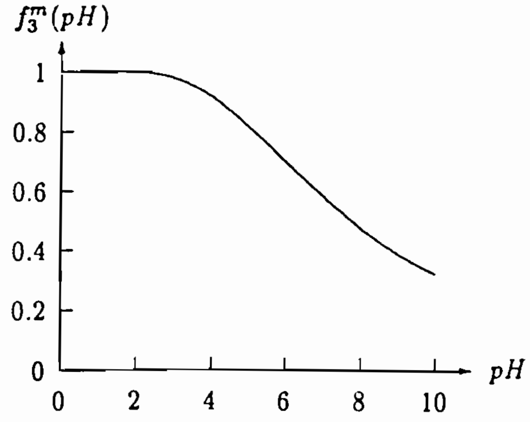
* 1 are model values; ** 2 are experimental values

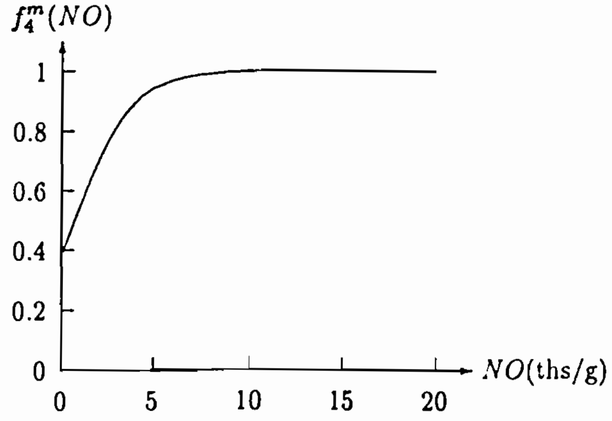




$$f_1^m(UK) = 1.050 \cdot UK^{0.0262} \cdot \exp(-0.103 \frac{UK}{2.34 - UK})$$

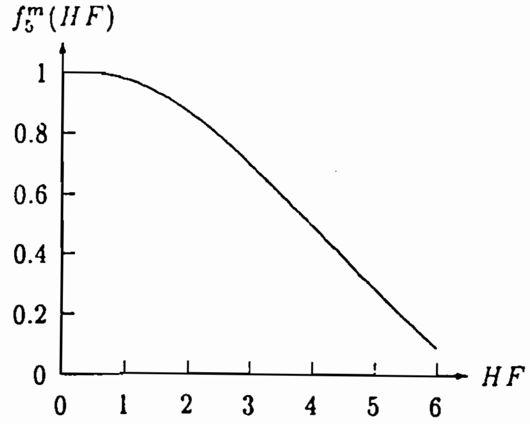
$$f_2^m(GL) = 1.0 - 0.98 \cdot (1.0 - \exp(-0.55 \cdot GL))^{1.49}$$

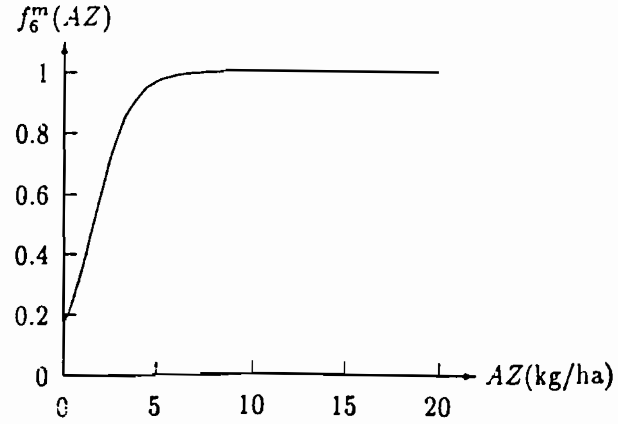




$$f_3^m(pH) = 1.0 - 0.859 \cdot (1.0 - \exp(-0.36 \cdot pH))^{8.49}$$

$$f_4^m(NO) = \frac{1.0}{1.0 + \exp(0.459 - 0.65 \cdot NO)}$$

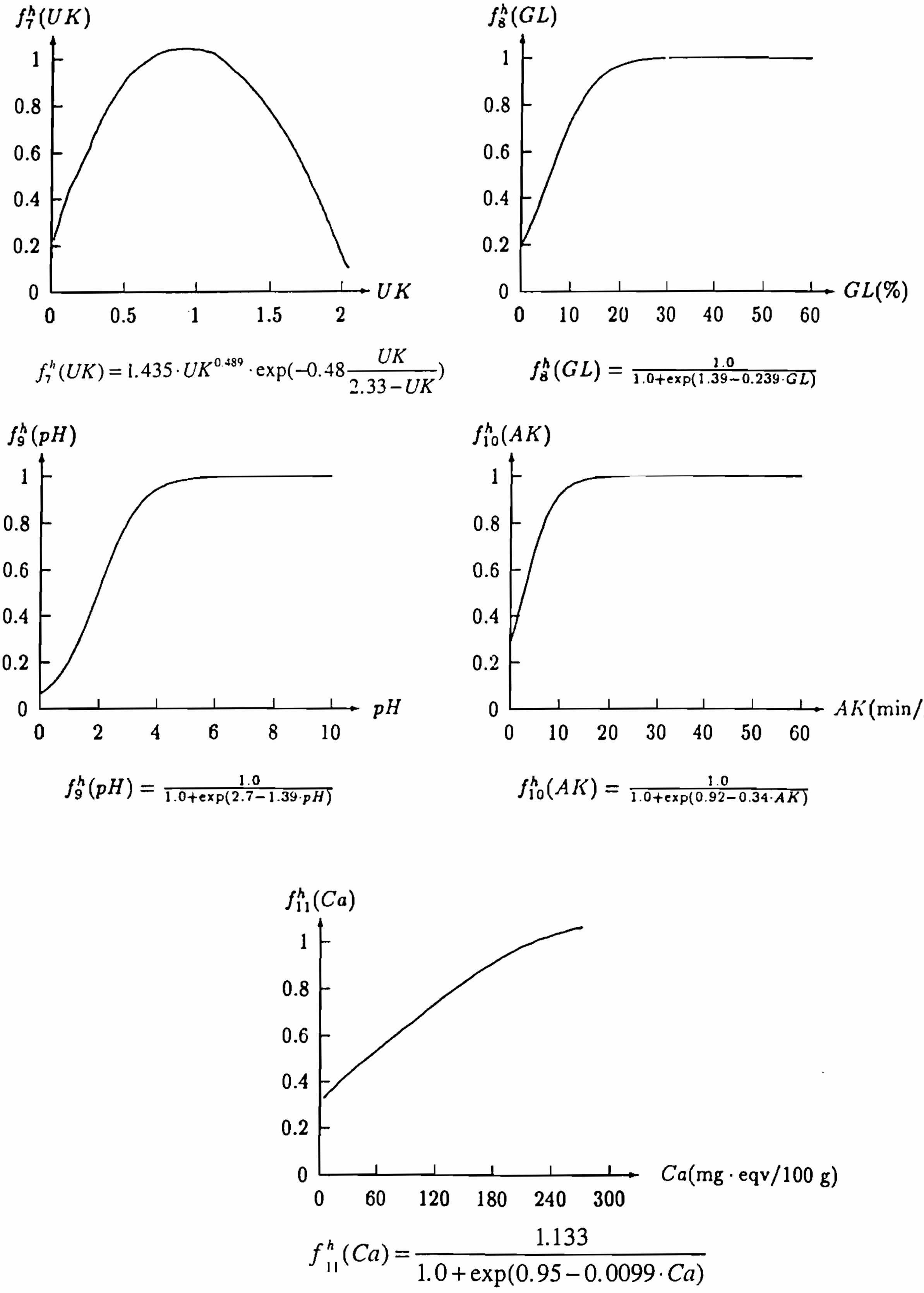




$$f_5^m(HF) = 1.0 - 1.8 \cdot (1.0 - \exp(-0.26 \cdot HF))^{2.89}$$

$$f_6^m(AZ) = \frac{1.0}{1.0 + \exp(1.59 - 0.35 \cdot AZ)}$$

Fig. 25 Partial response functions of humus mineralization.
For details of symbols used see the text.



$$f_7^h(UK) = 1.435 \cdot UK^{0.489} \cdot \exp(-0.48 \frac{UK}{2.33 - UK})$$

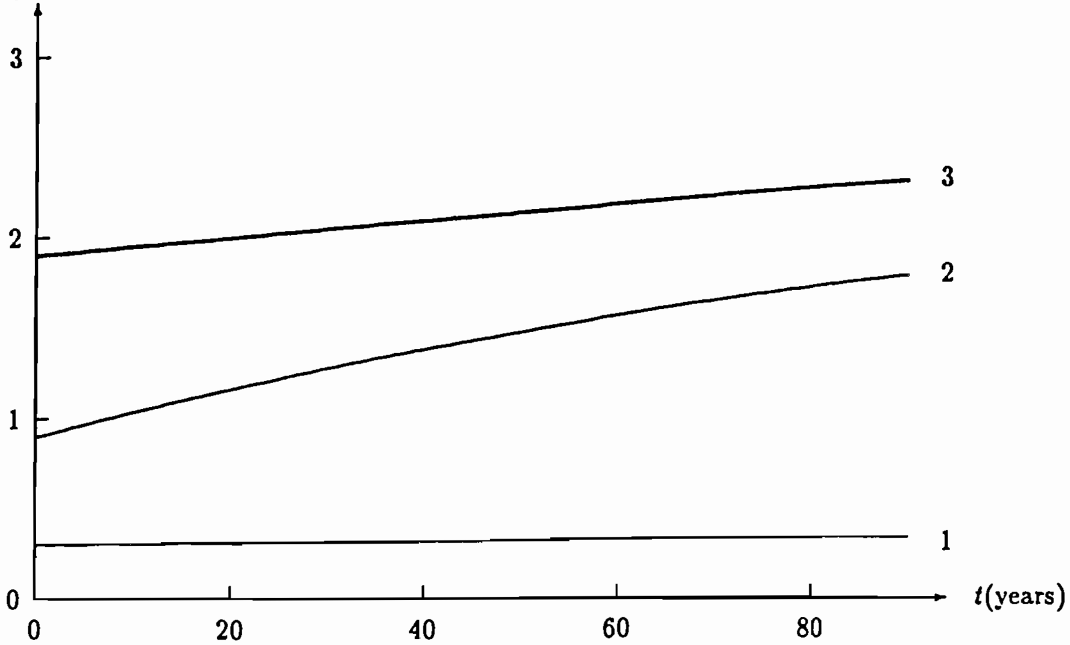
$$f_8^h(GL) = \frac{1.0}{1.0 + \exp(1.39 - 0.239 \cdot GL)}$$

$$f_9^h(pH) = \frac{1.0}{1.0 + \exp(2.7 - 1.39 \cdot pH)}$$

$$f_{10}^h(AK) = \frac{1.0}{1.0 + \exp(0.92 - 0.34 \cdot AK)}$$

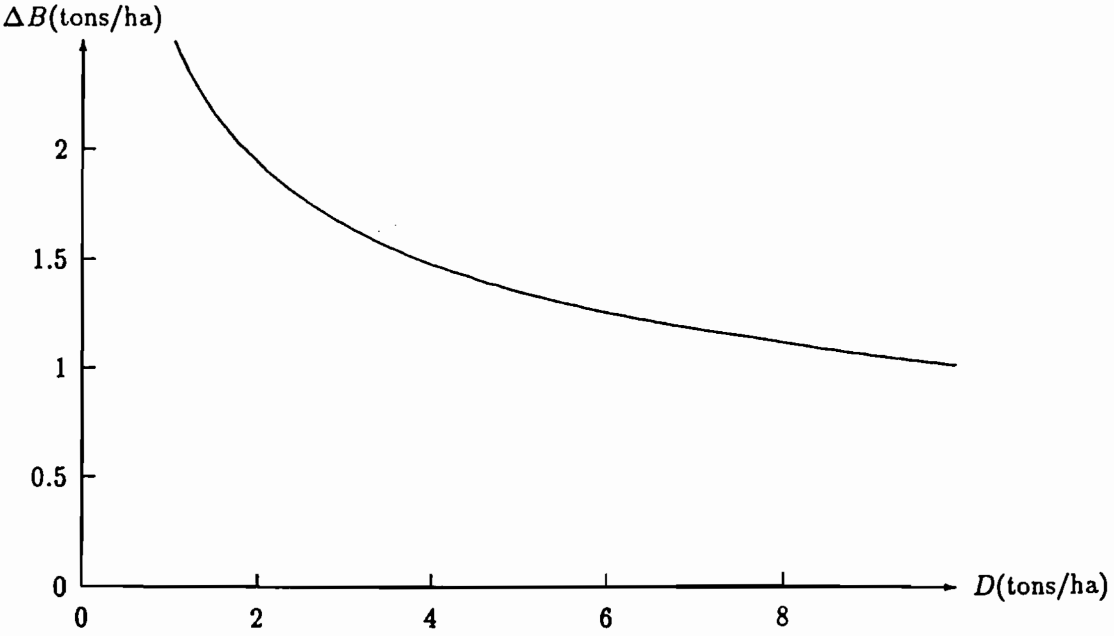
$$f_{11}^h(Ca) = \frac{1.133}{1.0 + \exp(0.95 - 0.0099 \cdot Ca)}$$

Fig. 26 Partial response functions of humification.
For details of symbols used see the text.



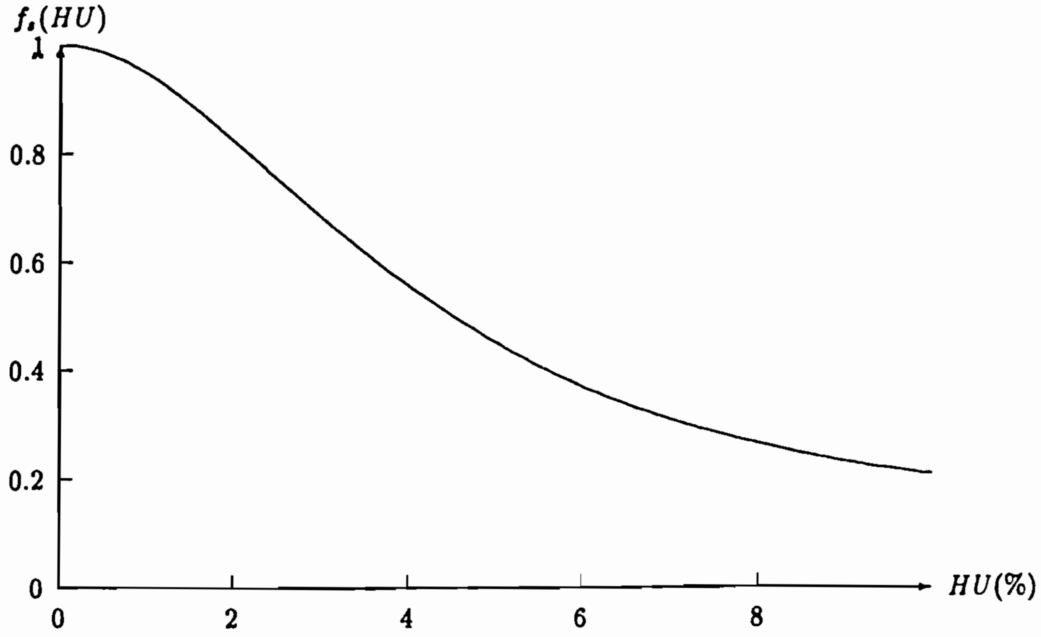
1. $C^{h/f}(D,t) = 0.3 + 0.9 \cdot (1.0 - \exp(-0.0005 \cdot D \cdot t))$
2. $C^{h/f}(D,t) = 0.9 + 1.6 \cdot (1.0 - \exp(-0.009 \cdot D \cdot t))$
3. $C^{h/f}(D,t) = 1.9 + 2.5 \cdot (1.0 - \exp(-0.002 \cdot D \cdot t))$

Fig. 27 Varying of ratio $C^{h/f}$ with annual manure D application (6 tons/ha) during 60 years in the various soil types:
1. sod podzolic; 2. grey forest; 3. ordinary chernozem



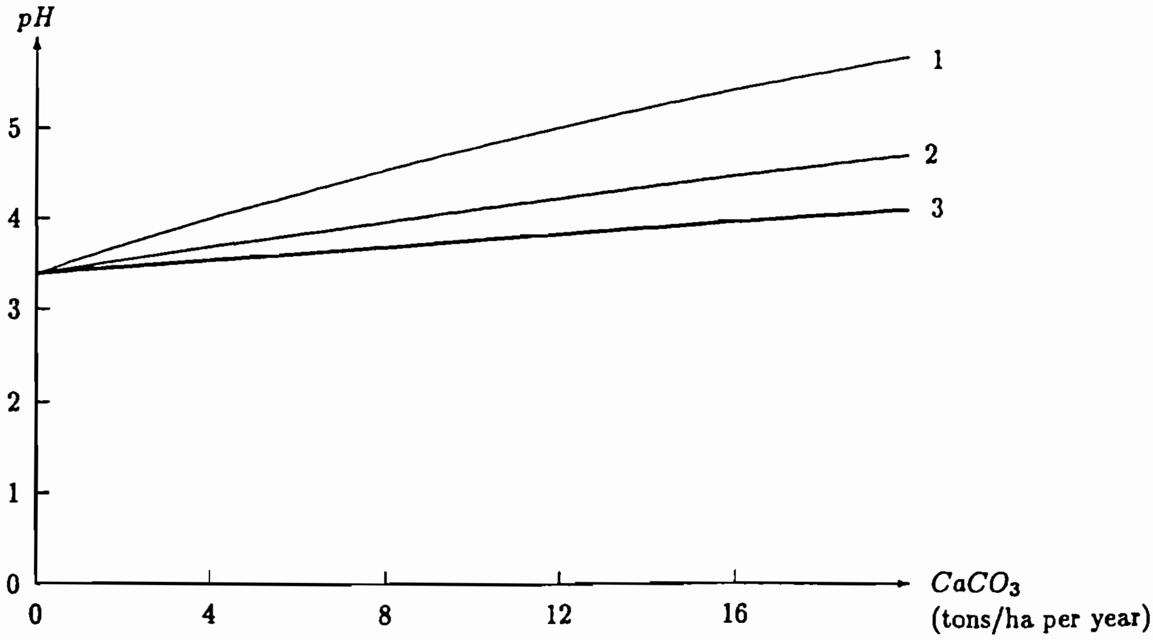
$$\Delta B(D) = 2.55 \cdot D^{-0.38} \cdot 2.361^{-0.006 \cdot D}$$

Fig.28 Added organic matter for humification in soil resulted from the various doses of manure application
(tons/ha dry matter per 1 ton of manure)



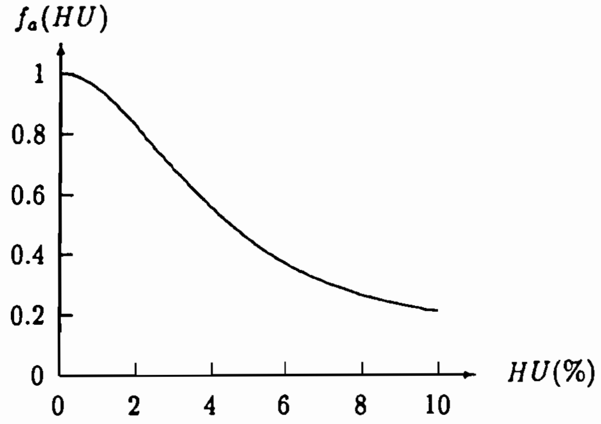
$$f_s(HU) = 1.0 - 0.849 \cdot (1.0 - \exp(-0.35 \cdot HU))^{2.29}$$

Fig. 29 Soil buffer capacity to liming depending on humus content $HU(\%)$



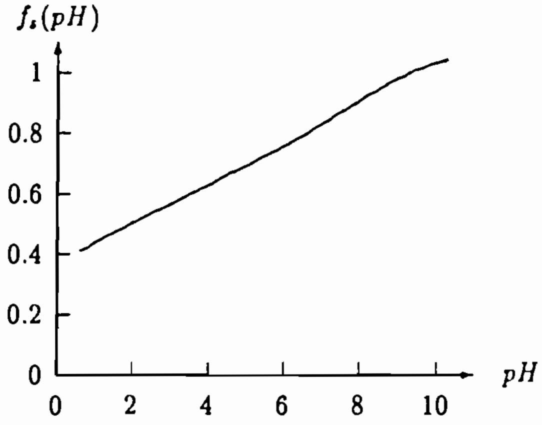
$$pH(Ca) = pH_{max}(1.0 - \exp(-0.035 \cdot f_s(HU) \cdot CaCO_3)) + pH_0$$

Fig. 30 Impact of various lime doses $CaCO_3$ (tons / ha per year) on the varying of soil acidity in the soils with various humus content : 1.- 1.2%; 2.- 5.25%; 3 - 9.8%.



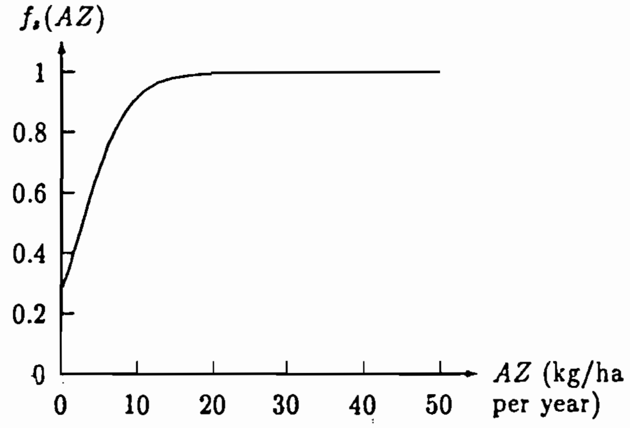
$$f_a(HU) = 1.0 - 0.849 \cdot (1.0 - \exp(-0.35 \cdot HU))^{2.29}$$

Fig. 31 The rate of soil acidification resulted from the mineral fertilizers application as depending on humus content $HU(\%)$.



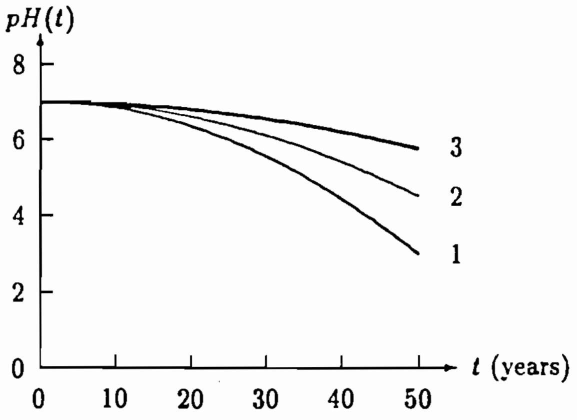
$$f_t(pH) = 1.234 \cdot \left(\frac{1.0}{0.977 + \exp(1.38 - 0.2 \cdot pH)} - 0.15\right)$$

Fig. 32 The rate of soil acidification resulted from the mineral fertilizers application as depending on the current soil acidity.



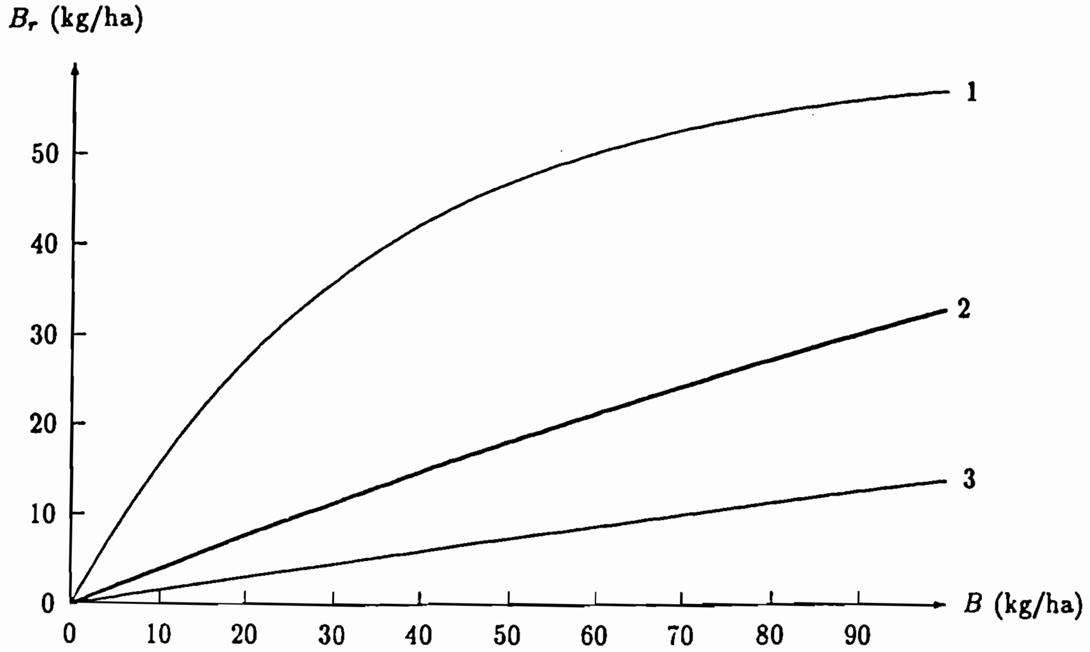
$$f_t(AZ) = 0.977 \cdot \left(\frac{1.0}{0.99 + \exp(0.9 - 0.34 \cdot AZ)} - 0.013\right)$$

Fig. 33 The rate of soil acidification resulted from the annual application of mineral fertilizers AZ (kg / ha per year).



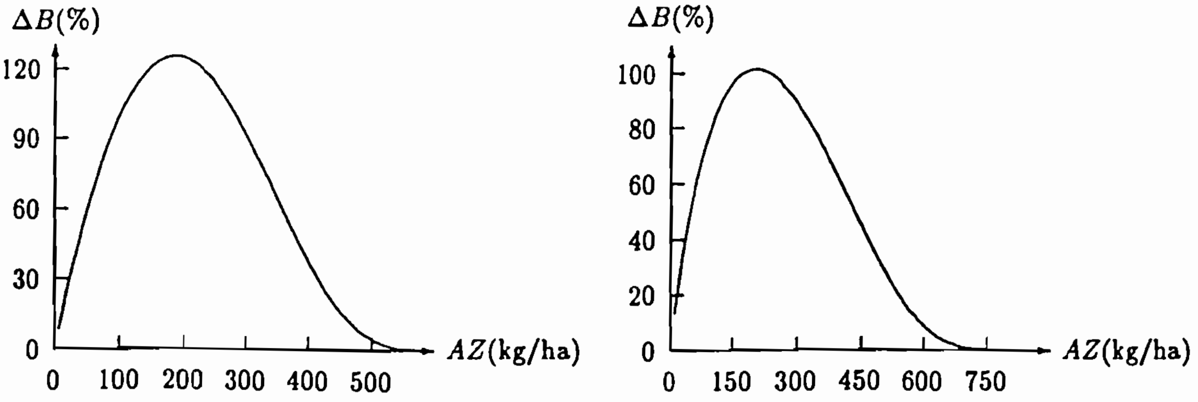
$$pH(t) = pH_0 \exp(-0.0129 \cdot f_a(HU) \cdot f_t(AZ) \cdot f_t(pH) \cdot t)$$

Fig. 34. Acidification of various soil types after 50 years of 130 kg/ha annual application of mineral fertilizers. Soil humus content: 1. 1.0%; 2.- 5.0%; 3.- 9.0%.



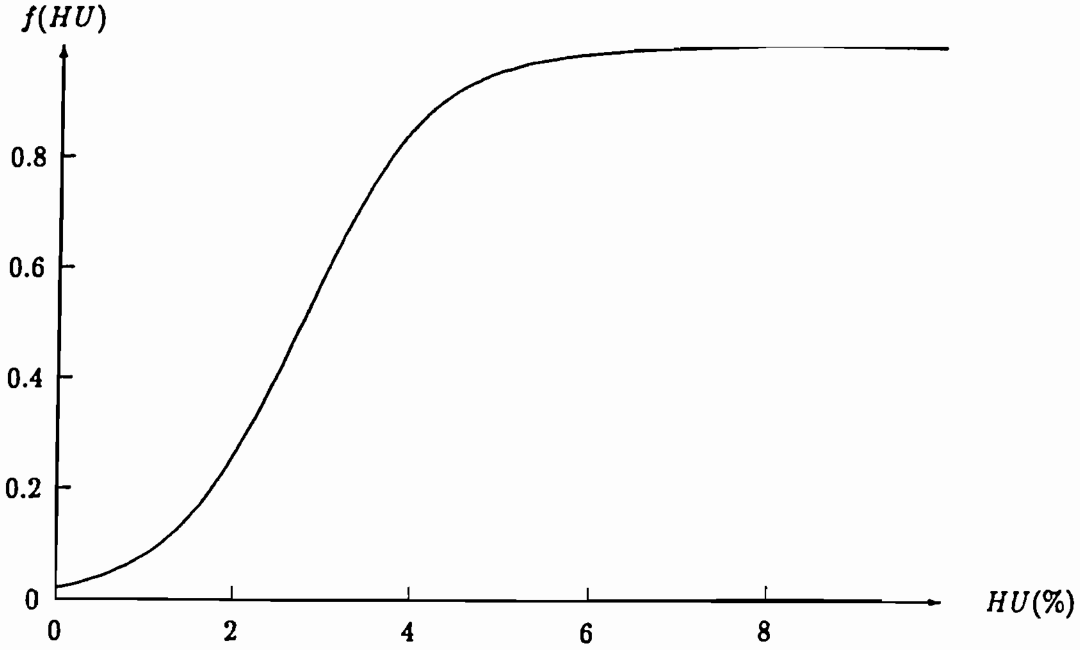
1. $B_{r1}(B_1) = 59.9 \cdot (1.0 - 1.5^{-0.075 \cdot B_1})$
2. $B_{r2}(B_2) = 64.9 \cdot (1.0 - 2.5^{-0.0026 \cdot B_2})$
3. $B_{r3}(B_3) = 99.9 \cdot (1.0 - 1.9^{-0.0062 \cdot B_3})$

Fig. 35 . Dependence of plant debris B_r (kg/ha) on the yield B (kg/ha) for : 1.- spring/winter crops; 2. potato; 3. grasses.



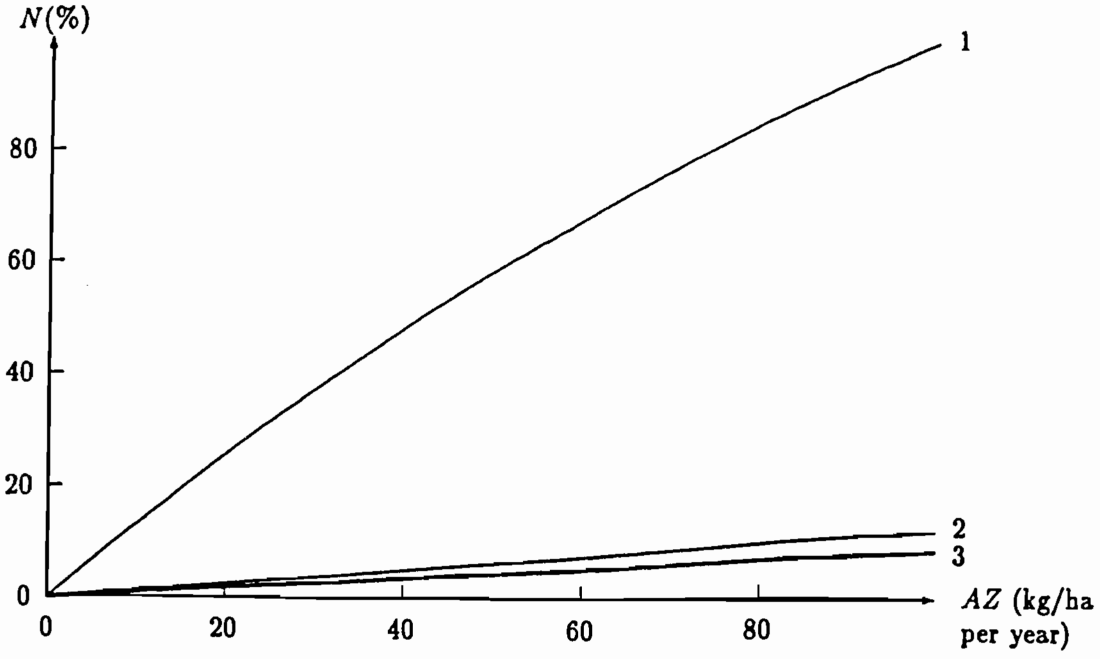
$\Delta B(AZ) = 1.5 \cdot AZ^{0.975} \cdot 2.058^{-2.9(\frac{AZ}{724.3-AZ})^{1.07}}$ $\Delta B(AZ) = 2.0 \cdot AZ^{0.88} \cdot 5.79^{-1.35(\frac{AZ}{924.3-AZ})^{0.91}}$

Fig. 36 . Increase of crop's yield ΔB (% from non - fertilized) resulted from the application of various doses of mineral fertilizers AZ (kg / ha per year) for spring wheat and potato.
a. potato b. spring wheat



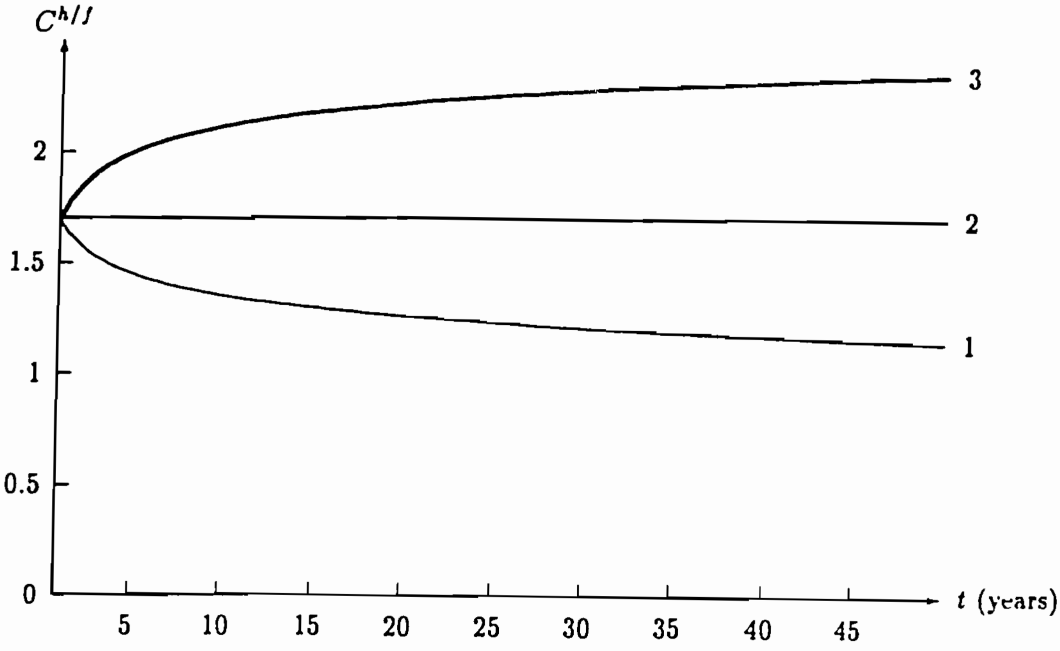
$$f\,(HU) = 0.999 \cdot \left(\frac{1.0}{1.0 + \exp(3.8 - 1.39 \cdot HU)} - 0.001\right)$$

Fig. 37 Soil nitrogen up-take as depending on soil humus content $HU(\%)$.



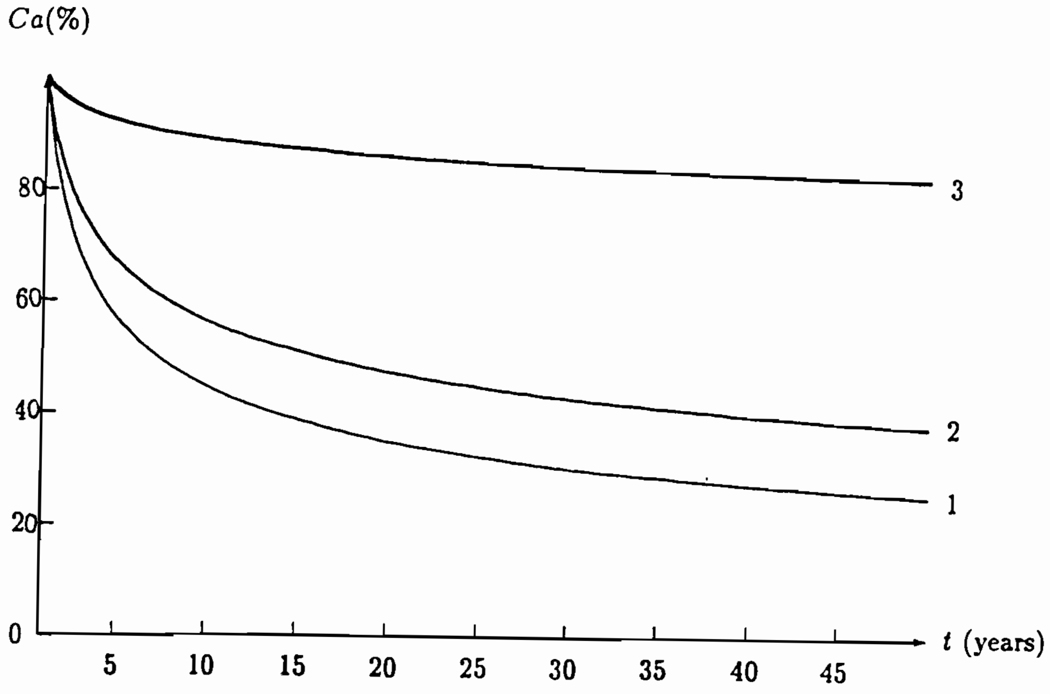
$$dN(AZ) = 200.0 \cdot (1.0 - \exp(-0.00043 \cdot \frac{AZ}{f(HU)}))$$

Fig. 38 The added soil nitrogen up-take N(% of non - fertilized) resulted from various doses of applied nitrogen AZ(kg / ha per year) as depending on humus content: 1.- 0.8 %; 2. -4.3%; 3.- 7.0%.



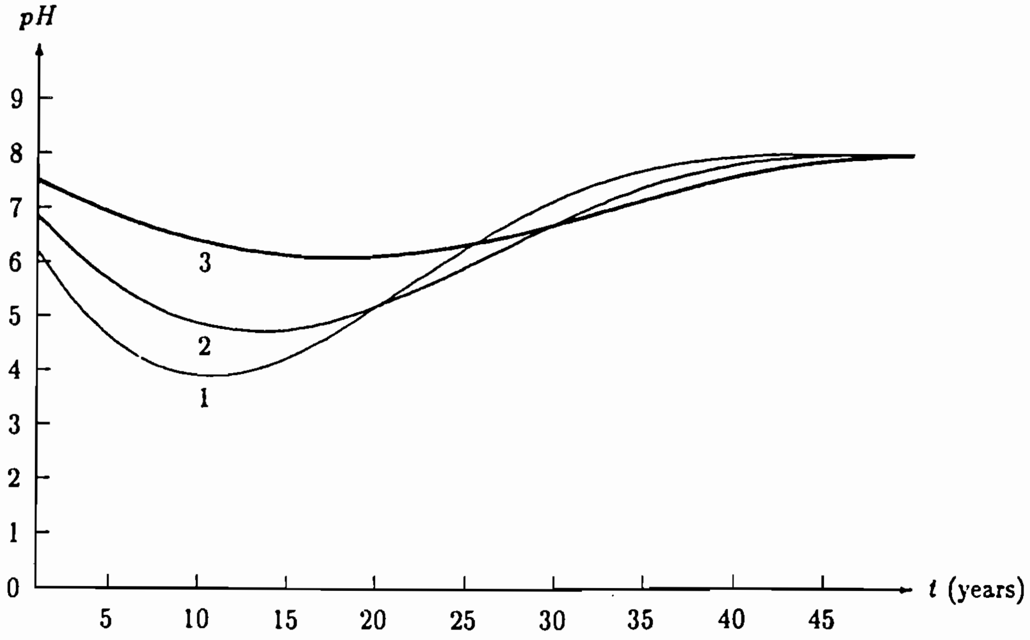
1. $C^{h/f}(t) = C_0^{h/f} \cdot \exp(-0.1 \cdot \ln(t))$; $k < 1$
2. $C^{h/f}(t) = const$; $k = 1$
3. $C^{h/f}(t) = C_0^{h/f} + C_{max}^{h/f} \cdot (1.0 - \exp(-0.1 \cdot \ln(t)))$; $k > 1$

Fig. 39 Varying of $C^{h/f}$ ratio as depending on the quality of irrigation water: 1.- $k > 1$ is low ; 2. $k = 1$ is medium; 3.- $k < 1$ is high quality.



1. $Ca(t) = Ca_0(t) \cdot \exp(-0.3 \cdot \ln(t))$; $k < 1$
2. $Ca(t) = Ca_0(t) \cdot \exp(-0.2 \cdot \ln(t))$; $k = 1$
3. $Ca(t) = Ca_0(t) \cdot \exp(-0.001 \cdot \ln(t))$; $k > 1$

Fig.40 . Varying of calcium cations (% of initial amount) contents in soil as depending on the quality of irrigation water . For details of symbols used see the legend to Fig. 15.

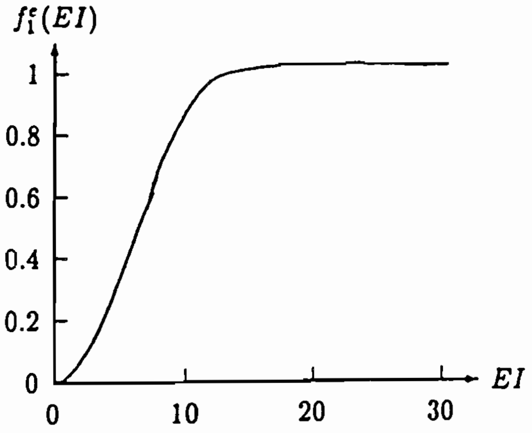


1. $pH(t) = 8.0 - 0.55 \cdot (t + 2.099)^{1.09} \cdot \exp(-3.906\frac{t}{65.0-t})$; $k < 1$

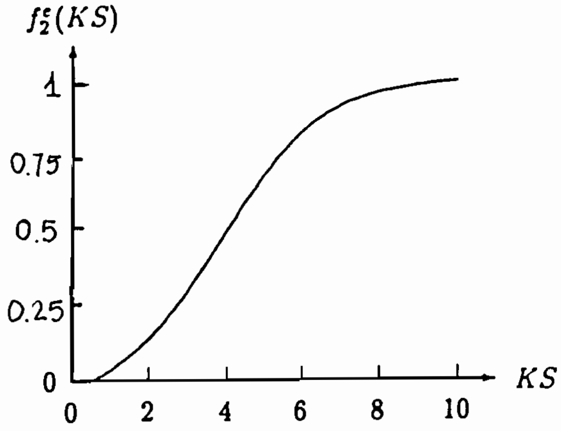
2. $pH(t) = 8.0 - 0.35 \cdot (t + 2.099)^{1.09} \cdot \exp(-2.906\frac{t}{65.0-t})$; $k = 1$

3. $pH(t) = 8.0 - 0.15 \cdot (t + 2.099)^{1.09} \cdot \exp(-1.906\frac{t}{65.0-t})$; $k > 1$

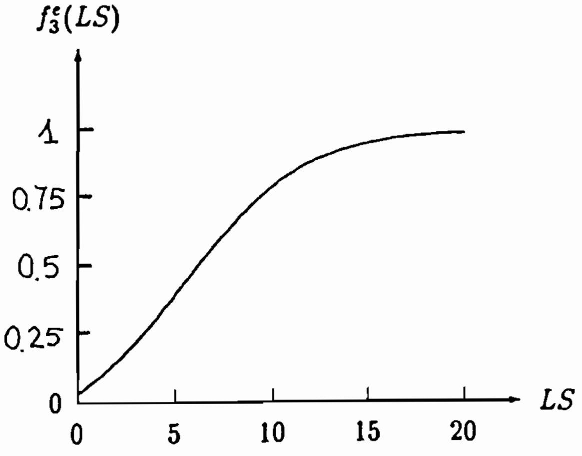
Fig. 41 . Varying of soil pH as depending on quality of irrigation water. For details of symbols used see the legend to Fig. 15.



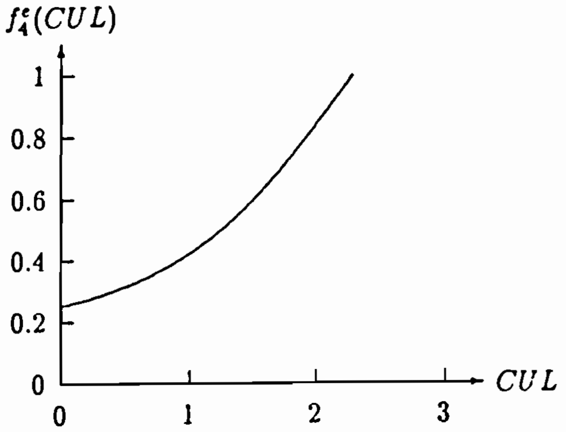
$$f_1^e(EI) = 1.169 \cdot \left(\frac{1.0}{1.08+\exp(2.87-0.51\cdot EI)} - 0.07\right)$$



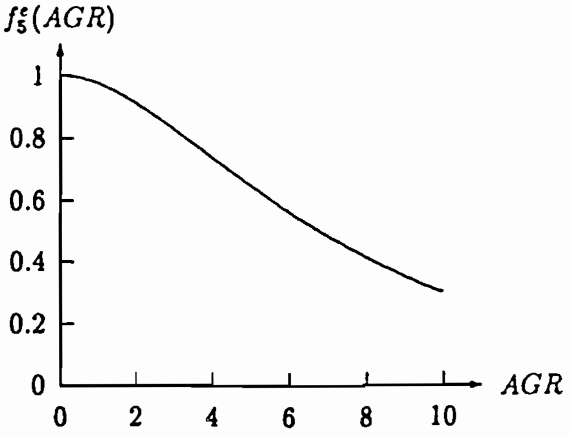
$$f_2^e(KS) = 0.252 \cdot \left(\frac{1.0}{0.27+\exp(1.5-0.74\cdot KS)} - 0.3\right)$$



$$f_3^e(LS) = 0.573 \cdot \left(\frac{1.0}{0.5+\exp(1.06-0.33\cdot LS)} - 0.24\right)$$

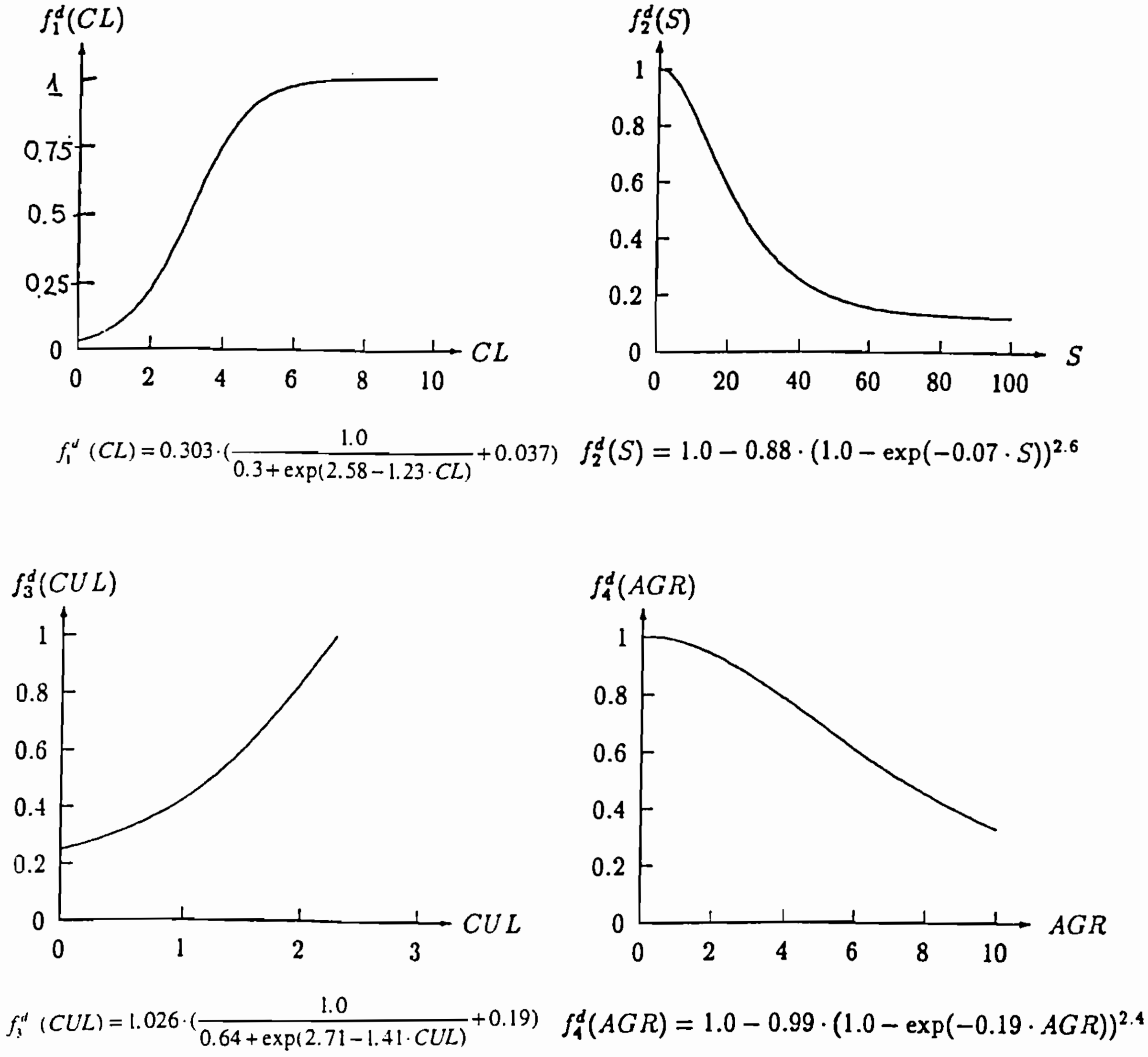


$$f_4^e(CUL) = \frac{1.0}{0.64+\exp(2.71-1.41\cdot CUL)} + 0.19$$



$$f_5^e(AGR) = 1.0 - 0.99 \cdot (1.0 - \exp(-0.19 \cdot AGR))^{2.1}$$

Fig. 42 . Partial response functions of soil water erosion.
For details of symbols used see the text.



$$f_1^d\ (CL) = 0.303 \cdot (\frac{1.0}{0.3 + \exp(2.58 - 1.23 \cdot CL)} + 0.037)$$

$$f_2^d(S) = 1.0 - 0.88 \cdot (1.0 - \exp(-0.07 \cdot S))^{2.6}$$

$$f_3^d\ (CUL) = 1.026 \cdot (\frac{1.0}{0.64 + \exp(2.71 - 1.41 \cdot CUL)} + 0.19)$$

$$f_4^d(AGR) = 1.0 - 0.99 \cdot (1.0 - \exp(-0.19 \cdot AGR))^{2.4}$$

Fig. 43 Partial response functions of soil wind erosion.
For details of symbols used see the text.

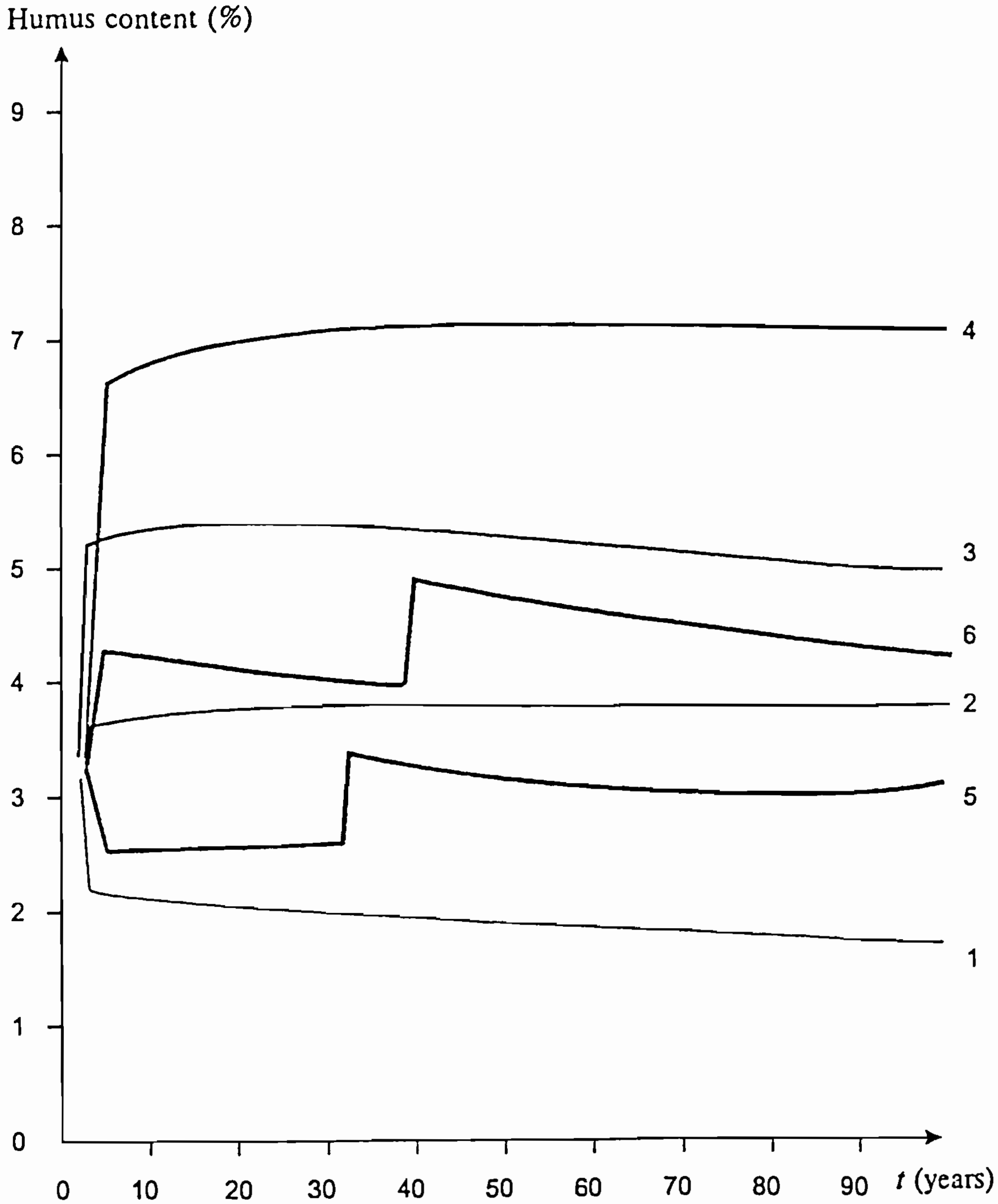


Fig. 44. Humus (%) dynamics in sod-podzolic soils resulted from various land-use practices. See the text for explanations.

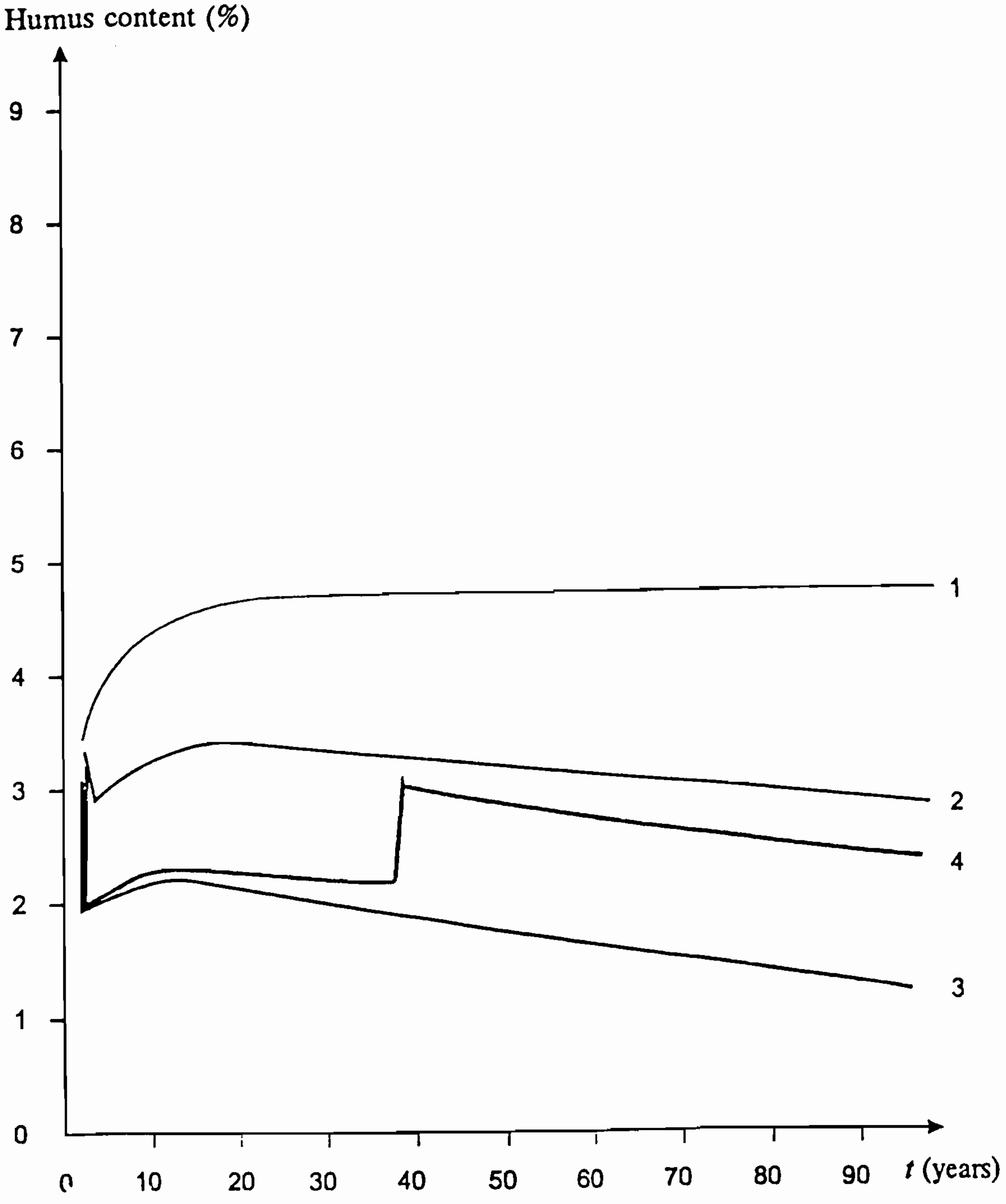


Fig. 45 Humus (%) dynamics in grey forest soils resulted from various land-use practices. See the text for explanations.

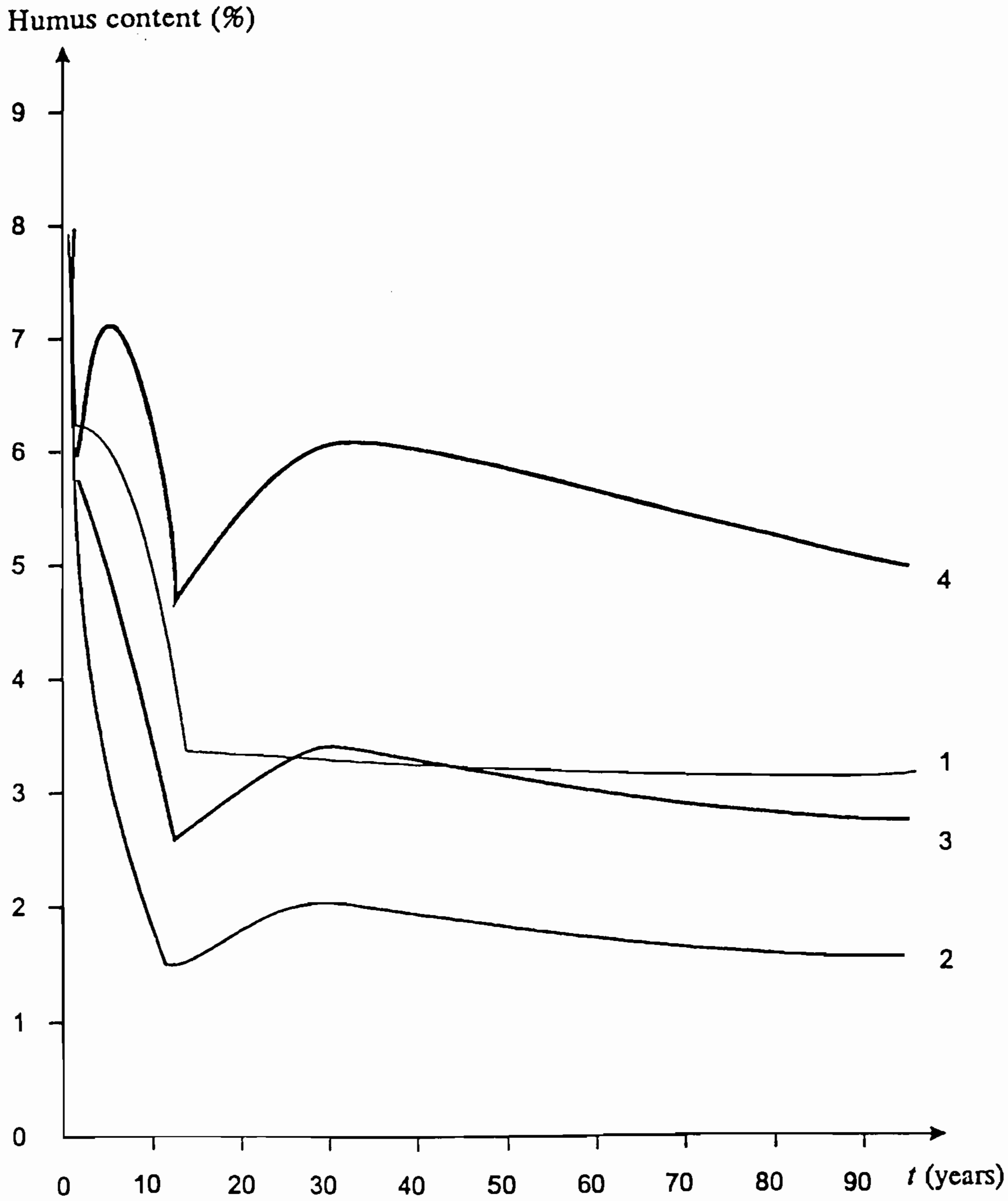


Fig. 46 Humus (%) dynamics in typical chernozems resulted from various land-use practices. See the text for explanations.

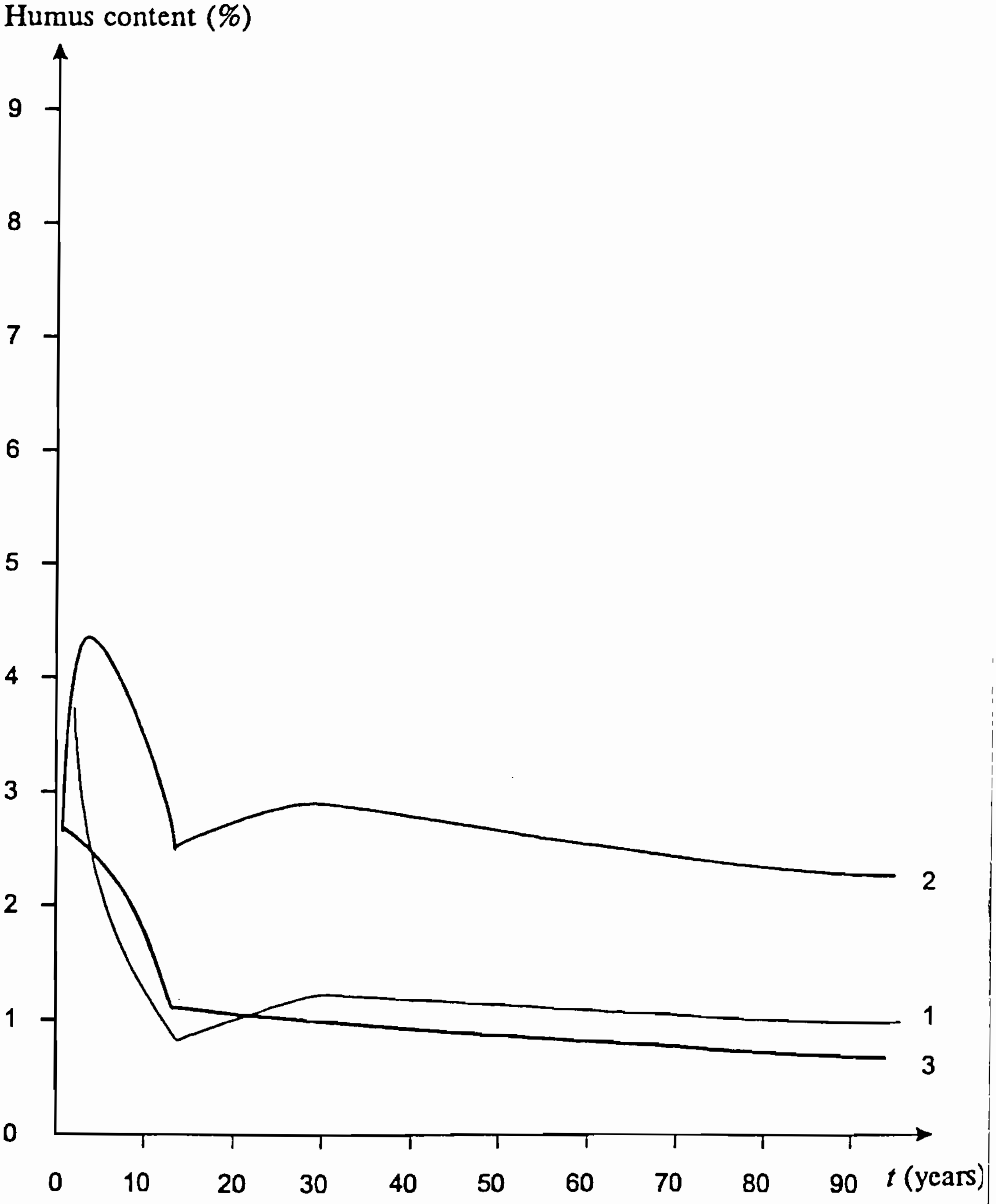


Fig. 47 Humus (%) dynamics in chestnut soils resulted from various land-use practices. See the text for explanations.

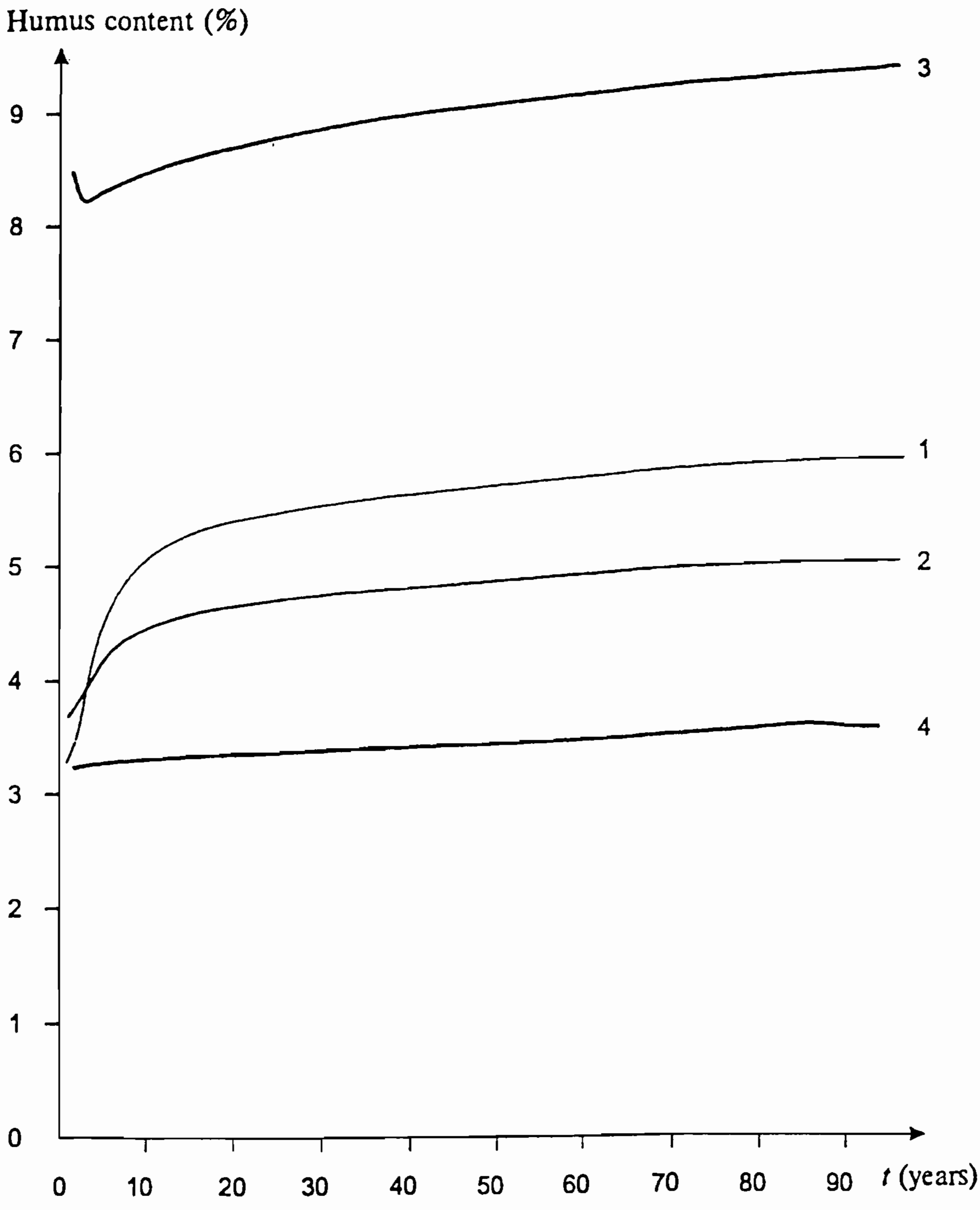


Fig. 48 Humus (%) dynamics in various soil types resulted from global climate change.:

1. Sod -podzolic soils;
2. Gray forest soils;
3. Typical chernozem;
4. Chestnut soils.

See the text for explanations.

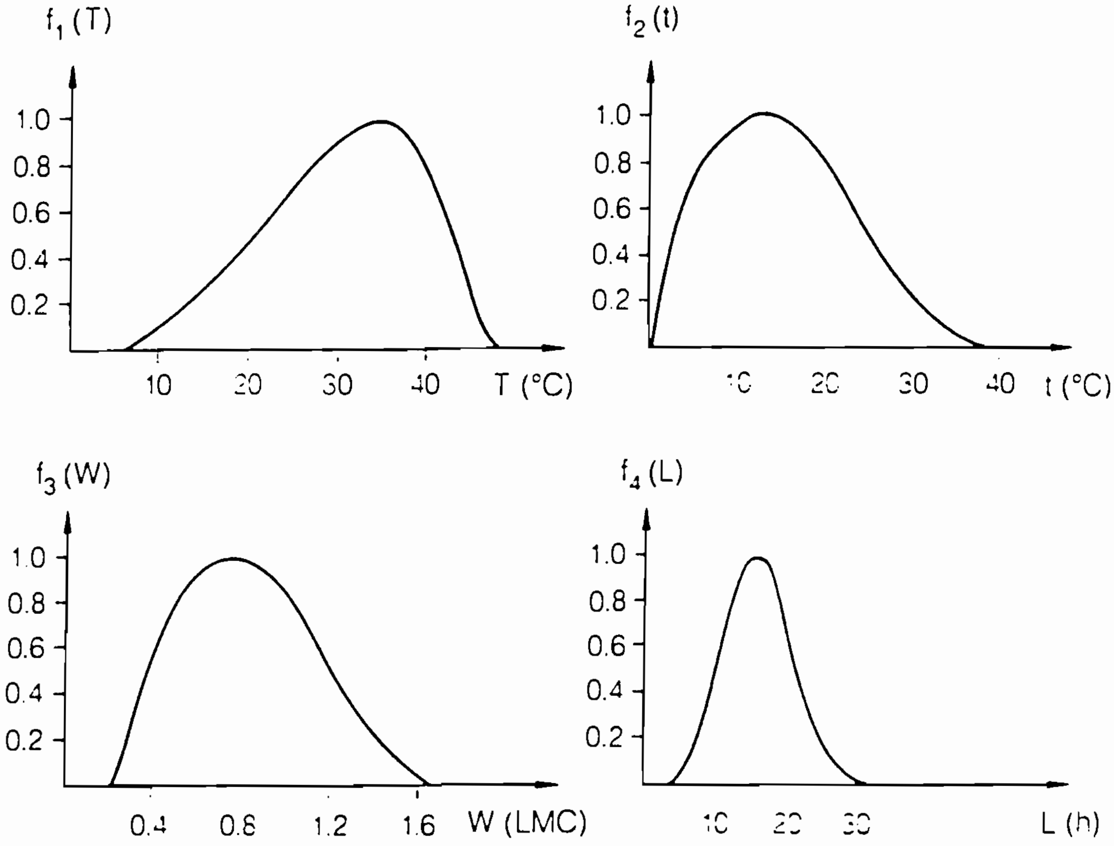


Fig. 49 The response functions of phenological development for the interphase stage of sprouting budding. *T*. Maximum daily air temperature: *t*. minimum daily air temperature: *W*. soil humidity: *L*. day length

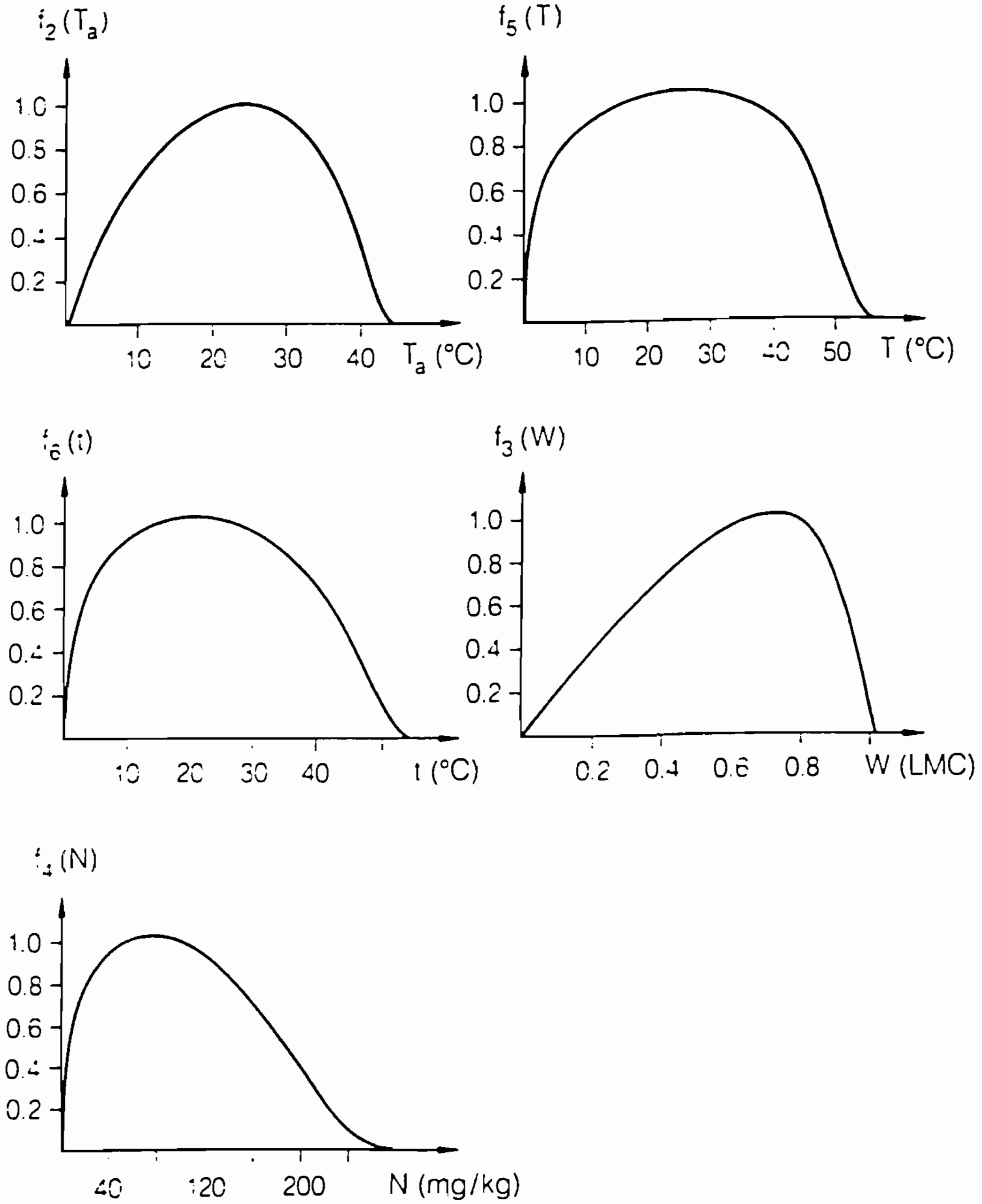


Fig.50 The response functions of growth rate for the interphase period milky ripeness-waxy ripeness. T_a. Average daily air temperature; N. available soil nitrogen content. See the legend to Fig. for further explanation

Table 4 Values of connection parameters of the submodel of phenological development

	i						
	T_{opt}	t_{opt}	W_{opt}	W_m	W_n	L_{opt}	$\bar{M}$
1	26.0	20.0	0.47	2.20	0.20	–	8
2	35.0	14.0	0.75	2.00	0.20	15.0	16
3	35.0	19.0	–	–	–	16.0	5
4	25.0	15.0	0.81	1.50	0.30	–	9
5	26.0	21.0	0.81	1.10	0.20	–	22
6	23.0	11.0	0.61	1.10	0.10	–	7
7	19.0	15.0	0.31	1.00	0.10	–	4

Table 5 Values of connection parameters of the submodels of growth and assimilate distribution

	i					
	2	3	4	5	6	7
d	0.625	0.625	0.625	0.570	0.400	0.400
α_1	165.6	156.2	188.4	148.6	130.9	110.3
ε	0.041	0.041	0.030	0.030	0.030	0.030
η	0.321	0.321	0.422	0.422	0.420	0.371
$T_{a\mathrm{opt}}$	19.45	19.45	20.72	25.71	25.93	26.01
T_{opt}	20.09	20.09	21.98	24.31	27.19	21.19
t_{opt}	11.05	11.05	15.82	19.43	21.04	17.22
W_{opt}	0.751	0.751	0.604	0.910	0.752	0.623
W_w	0.100	0.100	0.300	0.300	0.000	0.000
W_m	1.200	1.200	1.500	1.500	1.000	1.000
N_m	300.0	300.0	700.0	600.0	300.0	300.0
N_{opt}	35.0	35.0	60.0	145.0	70.0	70.0
ξ	–	–	–	0.007	0.002	0.002
ω	–	–	–	0.0003	0.0004	0.0006
W_m^s*	–	–	–	1.5	1.2	1.1
W_{opt}^s	–	–		0.5	0.75	0.7
W_w^s	–	–		0.2	0.1	0.1

* s, seed

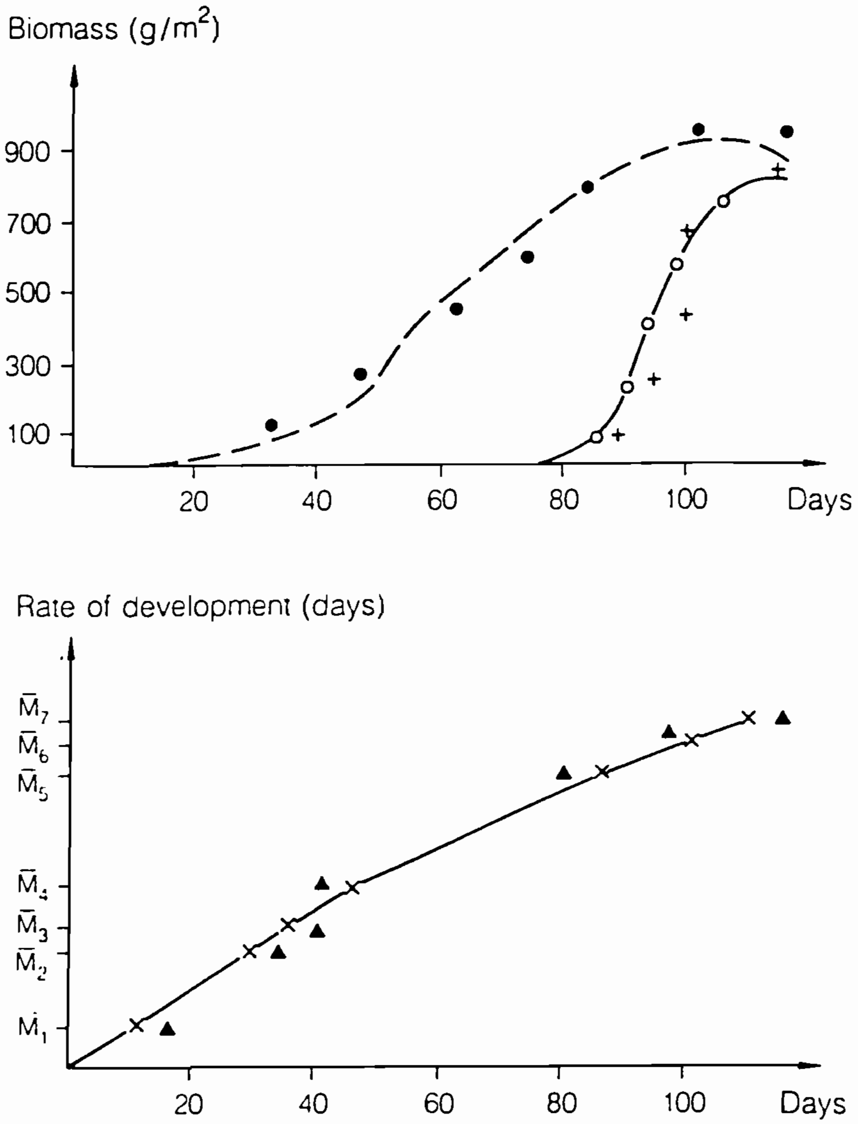


Fig. 51 The results of the testing of the model. Symbols used: , above-ground biomass (g/m^2); o , biomass of seed (g/m^2); × -, rate of development (days). Experimental data: ●, above-ground biomass; +, biomass of seeds; ▲, rate of development. $\bar{M}1$ $\bar{M}7$, mean length of interphase periods 1-7

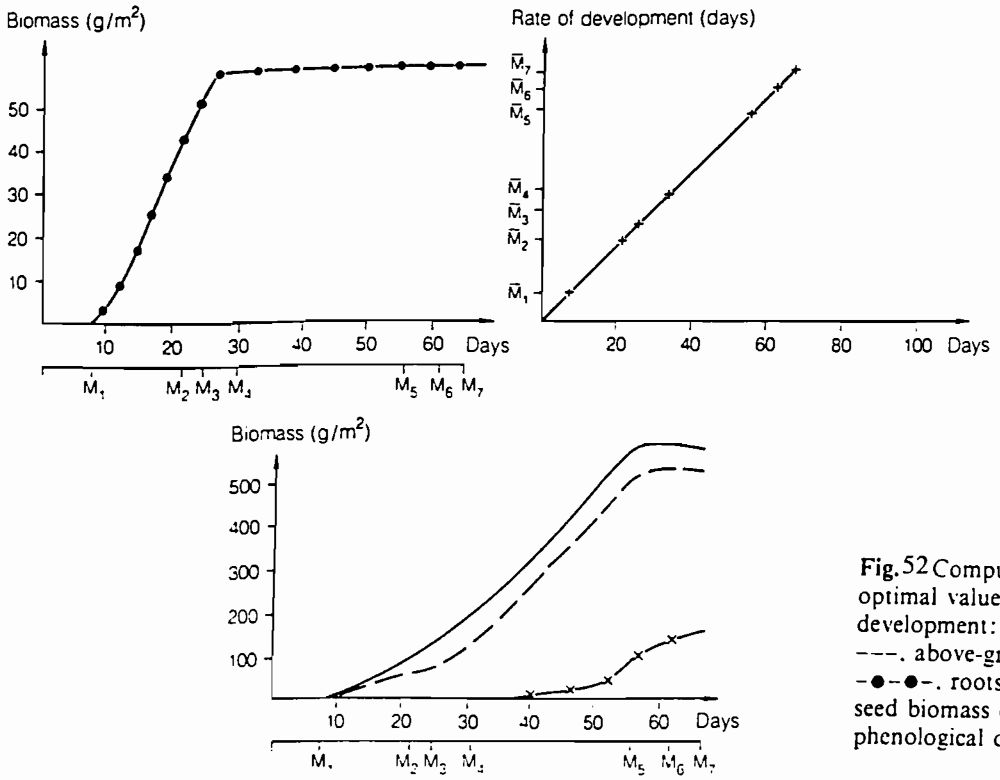


Fig.52 Computer simulation using optimal values of phenological development: ——, total biomass (g/m²); ---, above-ground biomass (g/m²); -●-●-, roots biomass (g/m²); -x-x-, seed biomass (g/m²); -+-+-, rate of phenological development (days)

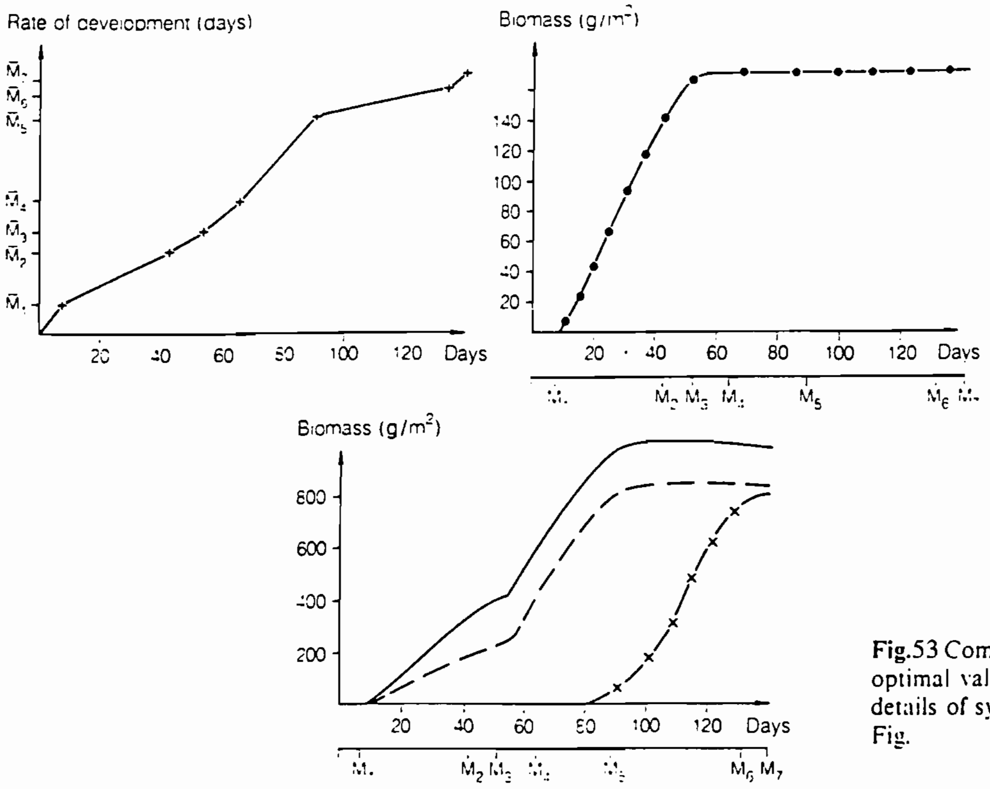


Fig.53 Computer simulation using optimal values of biomass growth. For details of symbols used see the legend to Fig.