1.1 Introduction

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Agriculture may be defined as the human activity that produces useful organic material by means of plants and animals, with the sun as the source of energy. The minimum required number of resources is small: labour and land, with some sun and rain. For many soil types and climates, farming systems have been developed that enable subsistence in food, clothing, shelter and fuel, provided sufficient land is available. Unless conditions are very favourable, these farming systems do not produce much more than bare necessities. However, man is an animal species that thrives on brick and concrete and the development of civilisation is very much intertwined with that of urban life. To sustain a substantial non–farming population, the productivity of the farming population has to be much higher than its subsistence level. This is only possible if the non – farm sector produces industrial means of production for the farmers within an economic structure that provides sufficient incentives for their use.

Although a sharp distinction is not possible, these means of production may be classified as labour saving, yield increasing and yield protecting such as machines, fertilizers and pesticides, respectively. Only the yield protecting inputs require little energy for their manufacture and use, although their development would hardly have occurred independently of the chemical industry. With some exaggeration, modern agriculture could therefore be defined as the human activity that transforms inedible fossile energy (mineral oil and natural gas) into edible energy through plants, animals and the sun.

Up to World War II, the emphasis in agriculture in the U.S.A. was on mechanization. Horses were replaced by tractors, so that land that was used to grow food for horses could be used to cultivate crops for other purposes. In this way, the agricultural output of the nation as a whole increased considerably. The yield increases per hectare were, however, small: for wheat only about 3 kg ha^{-1} yr^{-1} as is seen in Figure 1. In Europe in the same period, more emphasis was given to increasing the productivity per unit of land. However, the results were not impressive: ranging from about 4 kg ha^{-1} yr^{-1} in the United Kingdom to 18 kg ha^{-1} yr^{-1} in the Netherlands.

A few years after World War II, the annual yield increase suddenly improved, reaching 50 – 80 kg ha^{-1} yr^{-1} as is illustrated in Figure 1 for the United States and the United Kingdom. In general terms, this persistent yield increase may be attributed to the simultaneous effect of soil amelioration, the use of fertilizers and the control of diseases, as well as to the introduction of varieties that were able to make good use of these increased inputs. In many regions, wheat yields are still so low that an absolute yield increase of 50 – 80 kg ha^{-1}

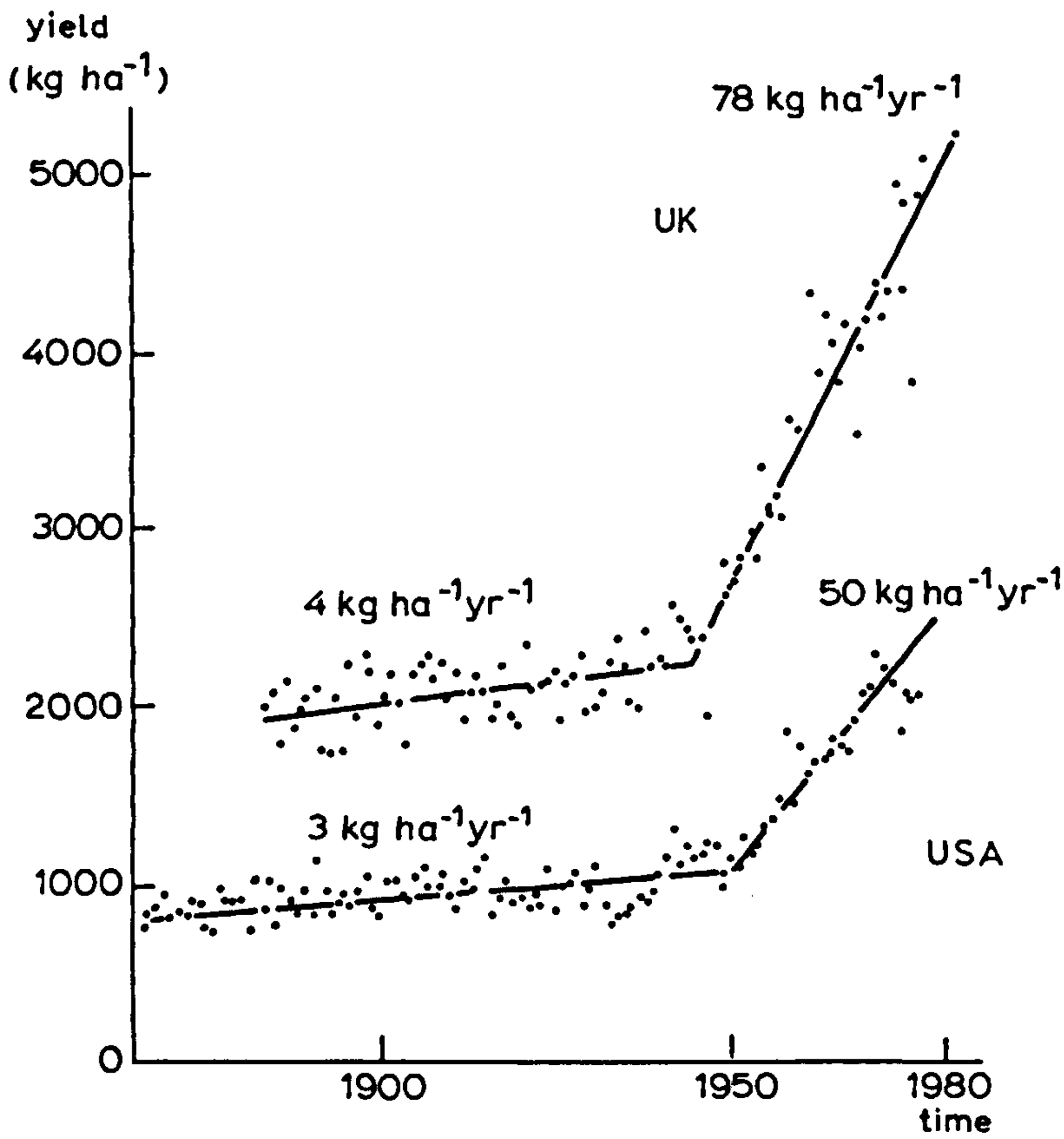

Figure 1. Average wheat yields in the United Kingdom and the United States over the last century.

yr^{-1} represents a relative increase of over 2 percent per year. The situation is not much different for other crops. Such yield increases outstrip the growth of the population in the industrialized countries. Any slack that is created in this way appears to be taken up by increased use of grain and land for milk and meat production and by taking land out of production.

In contrast, the annual yield increases in Africa, South America and Asia appear to be on an average 10, 19 and 25 kg ha^{-1} yr^{-1}, respectively (Figure 2). This is slightly higher than in the industrialized part of the world before World War II, which indicates that some of the knowledge and means of production are trickling down from North to South. However, this occurs at a rate that is too low to prevent hunger and malnutrition. For instance, in Africa with an average grain yield of 1000 kg ha^{-1}, the increase of 10 kg ha^{-1} yr^{-1} amounts to only 1 percent per year and even this may be too high an estimate for the last ten years. This growth in yield is far less than the relative growth rate of the population, which is 2–3 percent per year. Up to now, the difference has been more or less made up for by cultivating larger areas, but land that can be reclaimed by simple means within the social–economic framework of the family or the village is becoming scarce, so that more advanced technology is indispensable for further reclamation. Hence, to improve the food situation,

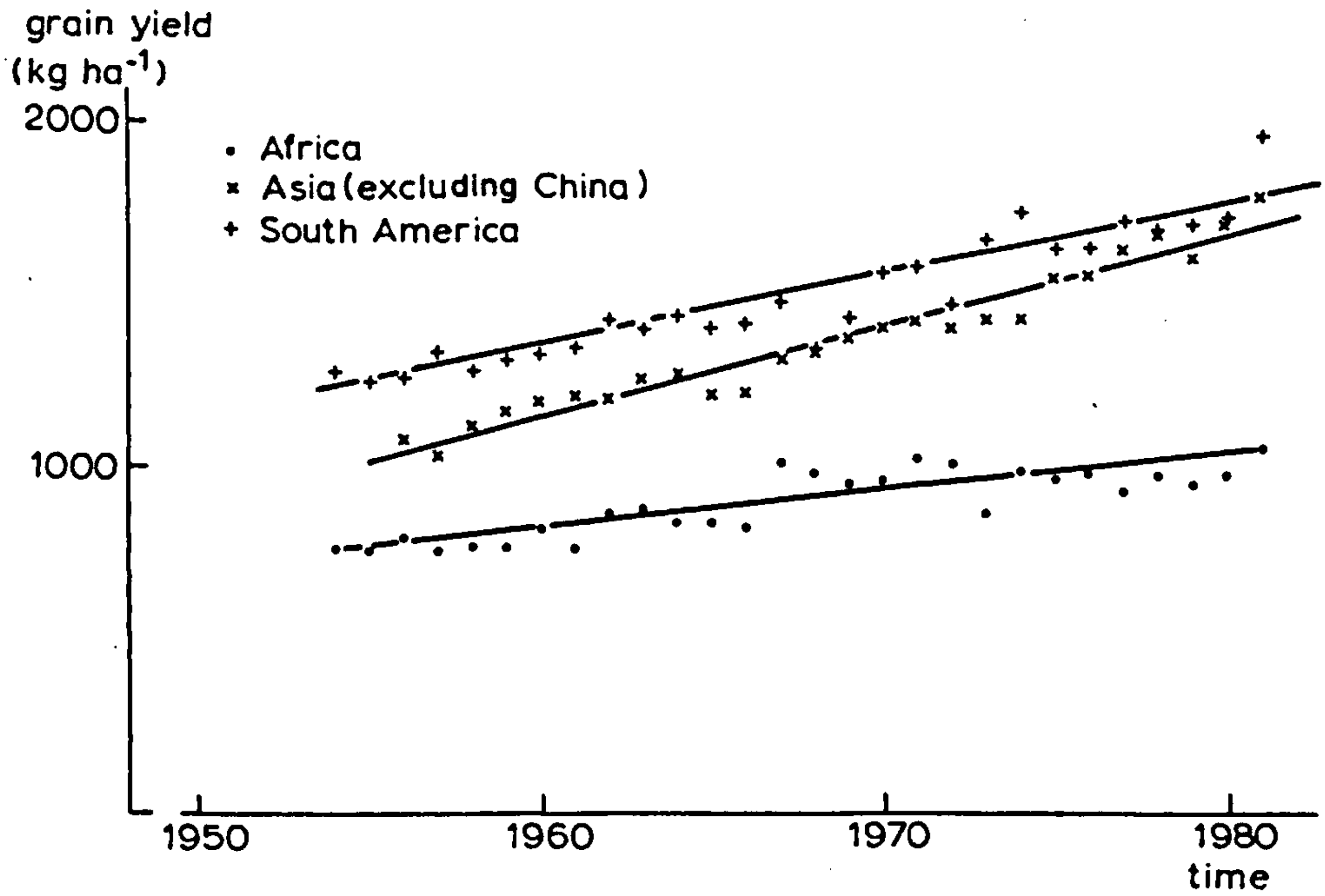

Figure 2. Average grain yields from 1954-1980 for Africa, Asia and South America.

either more machinery has to be used to extend the area under cultivation or more inputs, e.g. fertilizers, to increase the yield per unit area. Both of these paths require an open economy in which the farmer receives sufficient money for his agricultural products to pay for the necessary means of production. Too often the terms of trade are not so favourable, but claims that it is possible to improve substantially the food production in the world without these technical means are not justified in view of what is known about the agricultural production process.

Average yields, as used here for illustration, hide many differences. Some developing countries are reasonably well endowed with resources and have an economic structure that promotes agricultural development. Their price levels are such that it pays, at least for some farmers, to improve the soil, to apply fertilizers, to practise disease control and to use the proper plant varieties. However, policies that enable the poorest segments of the population to purchase the bare necessities may be lacking, so that hunger and malnutrition continue to exist. This is the case even in the richer countries of the world. There are also poor countries with infertile soils and an unfavourable climate, often with few other endowments and landlocked and with a demographic structure that results in rapid population growth. Such countries can only import the necessary agricultural inputs if they can export cash crops. Transport costs for both their import and export are often so high that even this path to increasing production is blocked. Then progress depends on political and economic solidarity that exceeds national boundaries.

The prospects for improvement of the food situation have, therefore, also national and international political and economic dimensions. International policy agreements aimed at stabilization of the prices on the world market at a fair level and at promotion of the opportunities of developing countries to penetrate the markets of the rich countries, may create a more favourable position for developing and poor countries. Such agreements must then be complemented by national development strategies that enable farmers to increase their output and, in particular, to improve the production opportunities for the poor. This broad range of problems has been the focus of research undertaken by the Centre for World Food Studies, which is situated in Amsterdam and Wageningen. For this research, national economic models with emphasis on the agricultural sector are being developed and linked to a global model to analyse and improve the policies of national governments and international agencies. These national economic models contain agricultural production modules that account for the possibilities of production and can distinguish between regions and commodities. That part of the work of the Centre focuses on the physical and agronomic factors that determine agricultural production and is the subject treated in this book.

The main purpose pursued is to familiarize the reader with the processes that govern the technical possibilities for agricultural production in a region in such a way that quantitative estimates can be made of the yield levels of the main crops under various constraints and of the inputs that are needed for their realization. The approach is necessarily simplifying, so the quantitative estimates should not be considered as the final answer, but rather as a framework for further analysis of possibilities and constraints that are based on factual knowledge, which can only be obtained by fieldwork.

For this approach, a hierarchical procedure is adopted which is in a schematic way presented in Figure 3. The rectangles in the second row represent the factors that ultimately determine the production potential. Climate and soil are fixed properties for a given region and, in combination with the level of reclamation, characterize the land quality level. The characteristics of agricultural crops may be changed by breeding, the scope for improvement in this respect being reasonably well – defined. For a given land quality level, the yield potential is therefore fixed for a fairly long period of time, and may, therefore, be calculated with reasonable accuracy.

In the further analysis, the goal is not to define a production function describing the relationship between the yield and all possible combinations of growth factors, because, by the nature of the agricultural production process, no unique solution to such a production function exists. Instead, a reasonable combination of growth factors should be established that will result in the yield level that is in accord with the land quality level. Thus, the yield level is considered concurrently as a dependent variable, determined by crop characteristics and land quality level, and as an independent variable, dictating the required input combination for its realization. This is reflected in the direction of the arrows in Figure 3: towards the yield level as well as away from the yield level.

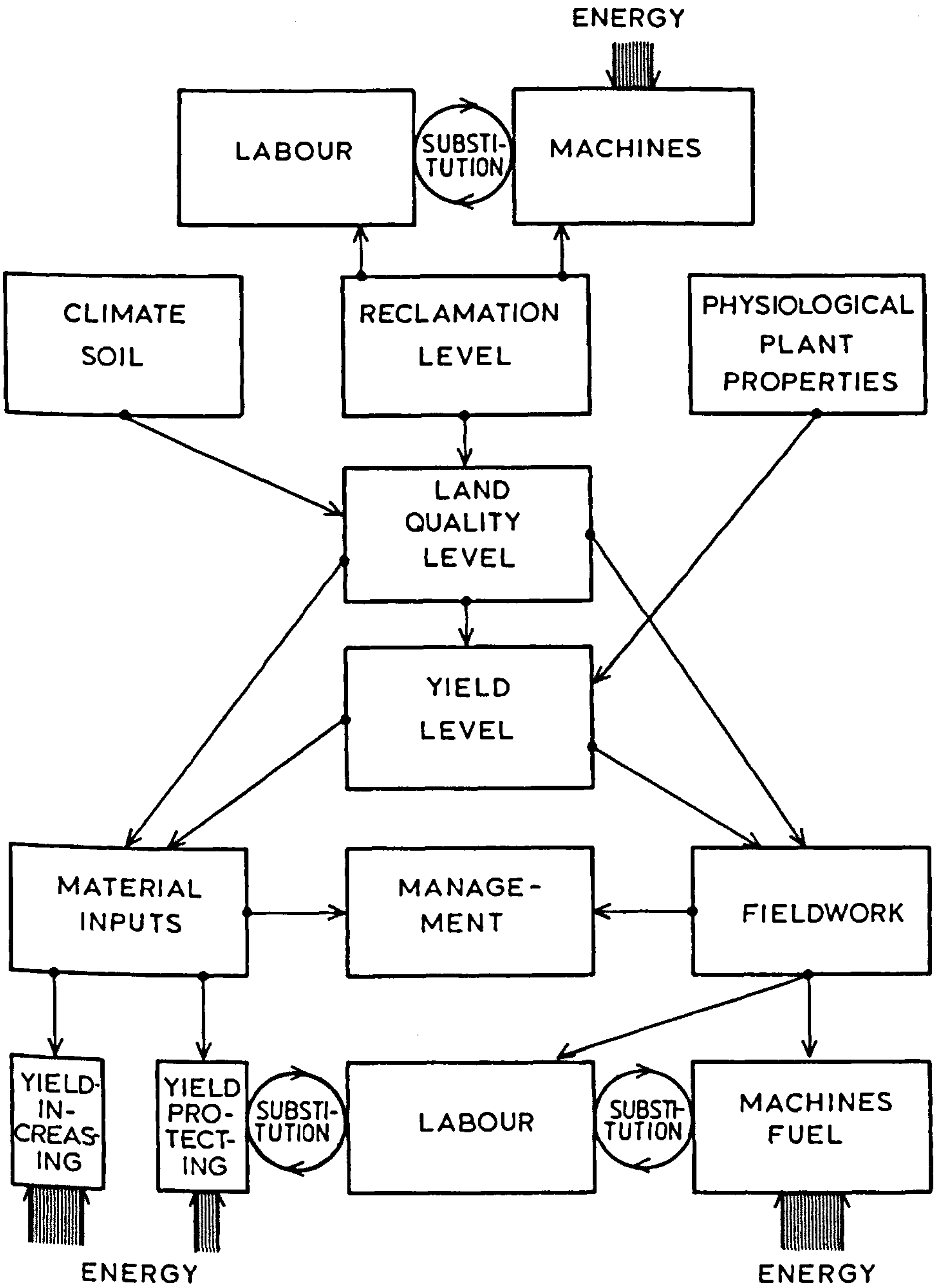

Figure 3. Schematic representation of the hierarchical analysis procedure.

With respect to the required inputs, a distinction is made between field work and material inputs. The necessary field work can be described in physical terms, for example, the requirements for ploughing, harrowing, weeding, the length of supply and transport lines, etc. The time required for these activities is to a large extent independent of the yield level as they must be done anyway. The total length of the period available to do the work depends, however, strongly on soil type and weather conditions. In performing field work, considerable substitution is possible between manual labour and activities relying on heavy mechanical equipment and their associated fossil energy requirements. The material inputs can be classified into yield – increasing inputs and yield protecting inputs. The required amounts of yield – increasing inputs such as water, minerals and nitrogen, are directly influenced by the required yield level, soil type and weather conditions. Characteristic for these inputs is that they cannot be substituted for by labour. This is in contrast to the yield protecting inputs, biocides, for which alternatives are available, i.e. labour – intensive weeding versus the use of herbicides and manual insect eradication versus insecticides.

The land quality level is, on the one hand, determined by intrinsic soil properties and the prevailing weather conditions and, on the other hand, by the level of reclamation. In a schematized set up, four levels of reclamation may be distinguished (Section 7.1). The lowest level refers to land in an almost virgin condition upon which agricultural activitities are limited to food gathering, fuelwood collection and extensive grazing. In the next level of reclamation, the land is cleared to allow more permanent agricultural use, with or without fallow periods. The moisture regime is fully dictated by weather conditions. Flooding, if any, can only be avoided by simple modifications of the topography or by building simple dams. The next level pertains to land upon which improvements have been carried out, such as levelling, simple terracing and the construction of open ditches to control excess water. The highest reclamation level refers to land in a favourable condition for crop growth, well levelled, with complete water control and the necessary infrastructure. Sufficient water is available for irrigation as required.

In addition to defining the present status of the land in a given region, it is also important to quantify the reclamation activities necessary to bring the land to a higher land quality level. This applies especially to the amount of vegetation and stones to be removed, the amount of soil to be moved and the infrastructure that must be built. This aspect of the analysis is represented in the first row (Figure 3). Reclamation can be carried out with manual labour. However, as has been stated above, this is often only a theoretical possibility, because most of the acreage that could easily be reclaimed has already been developed. Even in the People's Republic of China, it has been concluded that it is almost inevitable to resort to the use of mechanical means. The activities to be performed are therefore better defined for various technological levels in terms of the available equipment.

In the further analysis four hierarchically ordered production situations are distinguished. For the highest hierarchical production situation water, minerals, and nitrogen are in optimal supply. Crop yield is then only determined by the type of crop, the prevailing level of irradiance, and the temperature regime. Models to calculate potential growth (Section 2.1) and development (Section 2.2) of healthy closed green crop surfaces are available. Other models provide potential transpiration rates, so that the total water requirement may be obtained (Section 3.1). For most regions, sufficient experimental data are available to judge the feasibility of growing the major crops and to define so – called cropping calendars, which stipulate time of sowing, emergence, flowering, ripening, etc. (Section 6.1). Theoretical considerations and field data may be combined to develop simple calculation models for the relevant crops, yielding the time course of dry matter production and transpiration and the economic yield as outputs (Section 2.3).

For the second hierarchical production situation, it is assumed that the supply of nitrogen and minerals is still optimal, but the influence of moisture availability on transpiration and crop production is taken into account (Section 3.3). Water supply to the canopy is dependent mainly on rainfall and sometimes on supplementary irrigation. Water consumption is mainly determined by environmental conditions and the cover of the soil by the crop. The physical properties of the soil and the climatic conditions are now of major importance. From these data, the water balance is calculated. (Section 3.2). This enables determination of periods with excess or shortage of water, which will result in reduced growth rates compared with those for the first hierarchical level (Section 3.4). The models also enable the calculation of the number of workable hours in the field: an important parameter in the analysis of farming systems (Section 6.1).

For the third hierarchical production situation, apart from water and irradiance, the plant nutrients nitrogen and phosphorus may at times limit growth. Special emphasis is given to the use of nitrogen fertilizer, because of the large quantities required each year, it's cost and the mobility of nitrogen in the soil – plant – atmosphere system. The effect of nitrogen on production and the amount of nitrogen needed to achieve the production level of the second hierarchical production situation is determined by considering separately the relation between the amount of nitrogen that is taken up by the crop and the yield, and the relation between this uptake and the amount of fertilizer applied, or its recovery (Section 4.1). Phosphorus is treated in a similar fashion.

The recovery of nitrogen from fertilizer depends on the relative importance of the processes of uptake by the plants, mineralization from organic material, immobilization by soil – microbes, leaching and denitrification (formation of gaseous nitrogen). These processes are being modelled, but for the time being it is still necessary to rely also on the results of fertilizer experiments. This also holds for the determination of the amount of nitrogen that is available from natural sources. The recovery of phosphorus from fertilizer depends on such factors as the presence of soil constituents as aluminium and calcium in forms that render the phosphorus unavailable for the plants. The interaction between nitrogen and phosphorus fertilizer is treated by considering the P/N ratio in the plant tissue (Section 4.2). Whether minerals such as potassium, calcium and magnesium, are in sufficient supply and if the pH is in the proper range is most conveniently evaluated by means of soil analysis.

Subsistence farming is a concrete example of the fourth hierarchical production situation, i.e. hardly any external inputs are used. A generalized treatment may be based on the concept that under these conditions any farming system moves towards an equilibrium for the input and output of the main limiting growth factors (Section 6.2). The yield level at this equilibrium must be above a certain minimum to make the effort of farming worthwhile. Plant nutrients, especially nitrogen, ultimately limit the production in many situations. This implies that the effect of improved cultivation practices has to be judged on the basis of their temporal or permanent effects on the uptake of the limiting element. Since the possibilities to improve this situation are very restricted under conditions of low soil fertility, the effects of improved crop husbandry practices other than fertilizer application, cannot be cumulative, whether this concerns improved varieties, better cultivation or pest and disease control.

Of course, at any production level pests, diseases and weeds may interfere. Their effect is treated by making a distinction between diseases that are of special importance in high yield situations and those of special importance in low yield situations (Section 6.3). Different types of damage may be distinguished, which are evaluated in terms of damage levels.

This book is to a large extent based on the results of elaborate simulation models that have been developed in the past decade. Many of them have been described in other volumes of the Simulation Monograph series. For the present purpose these models have been simplified to such an extent that all calculations can be done with a simple scientific pocket calculator. For extended use this may be too cumbersome and for that reason a FORTRAN program is presented (Chapter 9), which allows the user to do the calculations on most home computers.

Any model, and certainly the computational schemes presented in this book are simplified representations of the complex real world. Therefore the results obtained should always be critically examined in the light of the practical experience and the results of field experiments, the more so if the crop is grown at the extremes of the range of conditions under which it is normally grown.