Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results

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Foreword

The collaboration between the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA) goes back more than 20 years, when FAO started a joint project on Land Resources for the Populations of the Future, completed in 1984. Since then, several collaborative programs were undertaken to underpin perspective studies that allowed prediction and estimates on how agriculture would develop toward the 21st century, and where problems were most likely to develop for achieving food security, particularly in developing countries. Those estimates, which are currently being revisited and extended in FAO's study "Agriculture towards 2015/30", have proved to be quite accurate, and are widely quoted and appreciated.

Originating from an internationally accepted Framework for Land Evaluation, the agro-ecological zones (AEZ) methodology enables rational land management options to be formulated on the basis of an inventory of land resources and an evaluation of biophysical limitations and potentials. The fact that digital global databases of climatic parameters, topography, soil and terrain, land cover, and population distribution are now more widely available has enabled revisions and improvements in AEZ calculation procedures. These data have also facilitated the expansion of AEZ crop suitability and land productivity assessments to temperate and boreal environments. Thus, the assessments of agricultural potentials are now truly global.

A major challenge facing any scientific analysis of complex societal issues is the communication of research results in a way that provides policy makers and the public with helpful and reliable insights. This report presents the methodology and global data sets applied in the assessment and demonstrates the regional potentials and limitations of land and biological resources. It also discusses various agricultural issues related to regional food security and sustainable resource development.

The report begins to address several key resource questions. Will there be enough land for agricultural production to meet food and fiber demands of future populations? Where do shortages of agricultural land exist, and where there is room for agricultural expansion? What contribution can be expected from irrigation? Is land under forest ecosystems potentially good agricultural land? What are the main physical constraints to agricultural production? Will global warming affect agricultural potentials?

It is hoped that the information presented in this report and the accompanying CD-ROM will contribute significantly to a sound use of scarce land resources, and to enhanced food security for all.

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Abstract

Over the past 20 years, the term *agro-ecological zones methodology*, or AEZ, has become widely used. However, it has been associated with a wide range of different activities that are often related yet quite different in scope and objectives. FAO and IIASA differentiate the AEZ methodology in the following activities:

First, AEZ provides a standardized framework for the characterization of climate, soil, and terrain conditions relevant to agricultural production. In this context, the concepts of “length of growing period” and of latitudinal thermal climates have been applied in mapping activities focusing on zoning at various scales, from the subnational to the global level. Second, AEZ matching procedures are used to identify crop-specific limitations of prevailing climate, soil, and terrain resources, under assumed levels of inputs and management conditions. This part of the AEZ methodology provides estimates of maximum potential and agronomically attainable crop yields for basic land resources units. Third, AEZ provides the frame for various applications. The previous two sets of activities result in very large databases. The information contained in these data sets form the basis for a number of AEZ applications, such as quantification of land productivity, extents of land with rain-fed or irrigated cultivation potential, estimation of the land’s population supporting capacity, and multi-criteria optimization of the use and development of land resources.

The AEZ methodology uses a land resources inventory to assess, for specified management conditions and levels of inputs, all feasible agricultural land-use options and to quantify anticipated production of cropping activities relevant in the specific agro-ecological context. The characterization of land resources includes components of climate, soils, and landform. The recent availability of digital global databases of climatic parameters, topography, soil and terrain, and land cover has allowed for revisions and improvements in calculation procedures. It has also allowed the expansion of assessments of AEZ crop suitability and land productivity potentials to temperate and boreal environments. This effectively enables global coverage for assessments of agricultural potentials.

The AEZ methodologies and procedures have been extended and newly implemented to make use of these digital geographical databases, and to cope with the specific characteristics of seasonal temperate and boreal climates. This report describes the methodological adaptations necessary for the global assessment and illustrates with numerous results a wide range of applications.

Acknowledgments

This important study would not have been initiated and carried out in its full breadth without the intellectual and financial support of FAO and the ample facilities made available in IIASA's Land Use Change (LUC) project. In particular we wish to acknowledge the foresight and the support of the respective former Directors of the Land and Water Development Division of FAO, Dr. Wim Sombroek and Dr. Robert Brinkman, and the current Acting Director of IIASA, Professor Arne Jernelöv.

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The Climate Research Unit's 0.5×0.5 degree latitude/longitude gridded monthly climate data has been supplied by the Climate Impact LINK Project (UK Department of the Environment, Contract EPG 1/1/16) on behalf of the Climate Research Unit (CRU), University of East Anglia.

We wish to express our sincere gratitude to our colleagues in the LUC Project at IIASA: to Ms. Sylvia Prieler for providing help with geographical information system (GIS) and data issues in numerous instances, and to Ms. Cynthia Enzlberger-Vaughan for editing various drafts of this report. We would also like to thank IIASA's Publications Department – including Eryl Maedel, Ewa Delpos-Kozubowski, Maggi Elliott, Anka James, and Lilo Roggenland – for help in preparing the manuscript for publication.

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Günther Fischer is the leader of the Land Use Change (LUC) Project at IIASA. A primary research objective of this project is the development of a GIS-based modelling framework, which combines economic theory and advanced mathematical methods with biophysical land evaluation approaches to model spatial and dynamic aspects of land-resources use. Previously, Fischer was principal investigator of the *World Agriculture, Environment and Land Use* Project and research scientist of the *Food and Agriculture Program* at IIASA. He participated in the formulation of a general equilibrium framework and the implementation and application of a global model of the world food system, known as IIASA's Basic Linked System. He was a major contributor to two studies of the Food and Agriculture Program: On welfare implications of trade liberalization in agriculture *Towards Free Trade in Agriculture*, and on poverty and hunger *Hunger: Beyond the Reach of the Invisible Hand*. Also, Fischer participated in several research projects on climate change and world agriculture. He was a member of the Core Project Planning Committee on Land-Use and Land-Cover Change (LUCC), under the International Geosphere–Biosphere Program and International Human Dimensions of Global Environmental Change Progam (IGBP–IHDP), and is a coauthor of the LUCC Science Plan. For six years he has served on the Scientific Steering Committee of the joint LUCC Core Project/Program of the IGBP–IHDP, and has been leading the LUCC Focus 3 office at IIASA.

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Acronyms and Abbreviations

AEZ	Agro-ecological Zones
AEZWIN	AEZ-based multiple criteria decision support system for land resources planning
AVHRR	Advanced Very High Resolution Radiometer
BLS	Basic Linked System of National Agricultural Policy Models (IIASA's world agricultural model)
CGCM1	Canadian Global Coupled Model, Canadian Centre for Climate Modelling and Analysis, Meteorological Service of Canada
CIESIN	Center for International Earth Science Information Network
CROPWAT	Computer Program for Irrigation Planning and Management, FAO, Land and Water Development Division
CRU	Climate Research Unit, University of East Anglia, Norwich, UK
DDC	Data Distribution Center of the IPCC
DEM	Digital elevation model
DSMW	Digital Soil Map of the World (FAO)
ECHAM4	Coupled Global Model, Max-Planck Institute for Meteorology and Deutsches Klimarechenzentrum, Hamburg, Germany
EROS	Earth Resources Observation Systems data center of the USGS
FAO	Food and Agriculture Organization of the United Nations, Rome, Italy
FAOCLIM	World-wide Agroclimatic Database, FAO, Rome
FAOSTAT	Food and Agriculture Organization of the United Nations Statistical Databases
FSU	Former Soviet Union
GAEZ	Global Agro-ecological Zones
GCM	General Circulation Models
GIS	Geographical Information System
GLASOD	Global Assessment of the Status of Human-induced Soil Degradation (UNEP/ISRIC)
GLCC	Global Land Cover Characteristics Database
GTOPO30	Global 30 arc-seconds elevation dataset
HADCM2	Coupled Global Model, Hadley Centre for Climate Prediction and Research, UK
IIASA	International Institute for Applied Systems Analysis, Laxenburg, Austria
IPCC	Intergovernmental Panel on Climate Change (WMO/UNEP)

ISRIC	International Soil Reference and Information Center, Wageningen, Netherlands
ISSS	International Society of Soil Science
IUCN	The World Conservation Union
JRC	Joint Research Centre of the European Commission
LAI	Leaf area index
LGP	Length of growing period
LUC	Land Use Change Project (IIASA)
LUT	Land utilization type
SLA	State Land Administration of the People's Republic of China
SOTER	Global and National Soils and Terrain Digital Database (UNEP/ISSS/ISRIC/FAO)
SRES	Special Report on Emission Scenarios (IPCC)
SSTC	State Science and Technology Commission of the People's Republic of China
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFPA	United Nations Fund for Population Activities
USGS	U.S. Geological Survey
WISE	World Inventory of Soil Emissions Potentials

1 Introduction

1.1 The Challenge of Sustainable Agriculture

The challenge of agriculture in the 21st century requires an integrated and systemic approach. This approach must address sustainable use and management of natural resources through development and adoption of farming technology and management practices that will ensure food security and agricultural livelihoods.

Over the next 50 years, the world population is projected to increase by some 3 billion, primarily in the developing countries. Yet, even today, some 800 million people go hungry daily, and more than a billion live on less than a dollar a day. Without social, economic, and scientific progress, more than a third of the world's expected 9 billion population could be living in poverty in the second half of this century. The current food insecurity and poverty affecting a fifth of the world's population is a sad indictment of the failure to respond adequately in a time of unprecedented scientific and technological progress and economic developments.

The need for food for an increasing population is threatening natural resources as people strive to get the most out of land already in production or push into virgin territory for new agricultural land. The damage is increasingly evident: arable lands lost to erosion, salinity, desertification, and urban spread; water shortages; disappearing forests; and threats to biodiversity. In the 21st century, we now face another challenge – perhaps an even more devastating environmental threat – of global warming and climate change, which could cause not only loss of production potential in many poor countries, but irreversible damage to land and water ecosystems.

Many of the most degraded lands are found in the world's poorest countries, in densely populated, rain-fed farming areas, where overgrazing, deforestation, and inappropriate use compound problems. When lands become infertile, traditional farmers either let the land lie fallow until it recovers, or simply abandon unproductive lands and move on, clearing forests and other fragile land areas as available. And the process is repeated.

Forests play a vital environmental role in the production of timber, wood, fuel, and other products; conservation of biodiversity and wild life habitats; mitigation of global climate change; protection of watersheds; and control of flood risks. More than a fifth of the world's land surface – some 3 billion hectares (ha) – is under forest ecosystems. Eight countries – Russia, Brazil, Canada, the United States, China, Australia, Congo, and Indonesia – account for 60% of the world's forest-land. During the past decade, some 127 million ha of forests were cleared, while some 36 million ha were replanted. Africa lost some 53 million ha of forest during this period, primarily from expansion of crop cultivation.

About 70% of the world's freshwater use goes to agriculture, a figure that approaches 90% in countries such as India and China, which rely on extensive irrigation. Already, some 30 developing countries are facing water shortages and by 2050 this number will increase to some 55 countries, the majority in the developing world. This water scarcity, together with degradation of arable land, could become the most serious obstacle to increasing food production.

The scientific and technological progress in just the last three decades, beginning with the Green Revolution of the 1970s, and continuing with the information revolution of the 1980s, and the genetic revolution of the 1990s, offers an unprecedented opportunity to reshape the productivity and sustainability of food and agricultural systems.

Thirty years ago, the world faced a global food shortage that experts predicted would lead to catastrophic famines. That danger was averted as an intensive international research effort enabled scientists to develop – and farmers to adopt – high yielding varieties of the major food crops. This "Green Revolution" was most effective where soils were fertile and water plentiful. It also entailed extensive use of fertilizers and pesticides.

World crop production increased at 2.2% per year, with yield increases contributing three-quarters of this growth and the other one-quarter coming from area expansion and increases in cropping intensity. More than a third of the increase in cereal production came from increased mineral fertilizer use. The fertilizer consumption in developed countries doubled from some 30 million tons of nutrients, while in the developing countries the corresponding increase was some twenty-fold from a low value of 4 million tons.

The world's total arable land in crop production amounts to 1.5 billion hectares, with some 960 million hectares under cultivation in the developing countries. During the last 30 years, world crop area expansion amounted to some 5.0 million hectares annually, and Latin American countries alone accounted for 35% of this global land expansion.

Critics of the Green Revolution stress that it benefited resource-rich farmers rather than the millions of small farmers, especially in rain-fed areas. The lessons of that Green Revolution indicate that an integrated biological, environmentally sound, and socially viable strategy has to be at the core of the next precision green revolution.

The information revolution can facilitate an interactive global agricultural knowledge system. For example, in the past, indigenous knowledge about local varieties, farming techniques, and natural resource management tested through the generations rarely made its way to scientists who could incorporate it in their work. Also, outputs of agricultural research and farming management experiences from around the world often took considerable time and effort to disseminate. All this and more can be done literally instantaneously with the tools of the Internet.

Biotechnology offers new tools for developing innovative crop varieties with attributes that can counter soil toxicity and droughts, resist pests and diseases, and increase the nutritive value of crops. These qualities are important to the poor and their crops. At the same time, questions of environmental risks and food safety will need to be resolved to ensure that the full potential of biotechnology and genetic engineering can be realized.

The advances in the geographical information system (GIS) and environmentally sound management of natural resources, the Internet and the information revolution, biotechnology and genomics will complement and enhance existing approaches, not replace them. In particular, it will be important to involve all stakeholders – farmers, researchers, agricultural extension services, policy makers and consumers – at the subnational and national level, in effective and efficient use of natural resources.

The range of uses that can be made of land for human primary needs is limited by environmental factors, including climate, topography, and soil characteristics. These uses are, to a large extent, also determined by agronomic viability and available science and technology as well as demographic, socioeconomic, cultural, and political factors, such as land tenure, markets, institutions, and agricultural policies.

Policy-makers and land users face the basic challenges of reversing trends of land degradation and inefficient water use in already cultivated areas by improving conditions and reestablishing their level of fertility, reducing deforestation, and preventing the degradation of land resources in new development areas through appropriate allocation and adequate use of resources for sustainable productivity.

Given the complex and interlinked components of the food security challenge in the 21st century, it is clear that solutions that deal with one part only – with crop productivity, for instance, or land use, or water conservation, or forest protection – will not be sufficient. The issues are connected and must be dealt with as an interlinked holistic system to ensure sustainable management of natural resources (FAO, 1995a).

Sustainable farming use must be based on sound agronomic principles, but it must also embrace understanding of the constraints and interactions of other dimensions of agricultural production, including the flexibility to develop a broad genetic base and to diversify. Both will help farmers respond quickly to changing conditions. Land management practices that can control the processes of land degradation, and their efficiency in this respect, will largely govern sustainability of a given land use (Smyth and Dumanski, 1993).

We do not know about future land use and agricultural production with certitude. For example, what agricultural technology will be available in the future and what will be its adoption rate and extent for various crops? What new genetic crop varieties will be developed? How will climate change affect crop areas and productivity? A scenario approach based on a range of assumptions related to such important changes in the future would enable assessments and a distribution of outcomes that facilitate policy considerations and decision making in the face of uncertainty.

Each country must give the highest priority to assessing its land, water, and climate resources and to creating an integrated system to apply the best of science, technology, and knowledge for sustainable agricultural development through informed policies and effective public and private investments and institutions.

1.2 Structure of the Report

FAO, in collaboration with IIASA, has developed the agro-ecological zones (AEZ) methodology and a worldwide spatial land resources database that enables an evaluation of biophysical limitations and production potential of major food and fiber crops, under various levels of inputs and management conditions.

The AEZ methodology follows an environmental approach: it provides a standardized framework for the characterization of climate, soil, and terrain conditions relevant to agricultural production. Crop modeling and environmental matching procedures are used to identify crop-specific environmental limitations under various assumptions.

When evaluating the performance of alternative land-use types, often the specification of a single objective function does not adequately reflect the preferences of decision-makers. These preferences are of a multi-objective nature in many practical problems dealing with resources planning. Therefore interactive multi-criteria model analysis has been introduced and applied to the analysis of AEZ models. It is at this level of analysis that socioeconomic considerations can effectively be taken into account, thus providing an integrated ecological-economic planning approach to sustainable agricultural development.

The report sets forth the AEZ methodology and its global results in six chapters, as follows. After this introduction (Chapter 1), an overview and the main steps in the application of the AEZ methodology are presented in Chapter 2. The AEZ approach is a GIS-based modeling framework that combines land evaluation methods with socioeconomic and multi-criteria analysis to evaluate spatial and dynamic aspects of agriculture.

The global AEZ resources database is composed of a digitized overlay of monthly climate attributes; FAO/UNESCO Soil Map of the World linking soil associations and attributes, elevation, and slope distribution; global land cover data – crops, forests, woodlands, wetlands; and spatial population distribution organized into grid-cells. A large amount of agronomic farm management data from around the world has also been incorporated.

The database contains some 2.2 million grid-cells (at 5' latitude/longitude), covering all countries' land resources. A grid-cell amounts to a land area of some 5,000 to 10,000 ha, depending on the latitude of a location. For each grid-cell, the assessment considers 28 possible crops at three levels of inputs, namely low, intermediate, and high. The high level assumes the best farming technology, soil nutrient inputs, and management known today. Future developments in new crop varieties and productivity can be incorporated into the scenario approach.

Chapter 3 discusses the characterization of climate resources in AEZ – thermal and moisture regimes – and soil and terrain resources and constraints, which together constitute the land resources inventory.

Chapter 4 describes land-use types, the procedures used to assess growing period and agro-edaphic suitability, and the calculation steps for determining crop biomass and yield.

Chapter 5 presents the AEZ results, with global coverage. These results are given in terms of regional summaries (*Tables 5.1* to *5.28*) and include quantification of land productivity; estimation of productivity and extents of land with rain-fed or irrigated cultivation potential; occurrences of environmental constraints, including temporal variability of climatic conditions to agricultural production; identification of potential "hot spots" of agricultural conversion, including forest areas; and possible geographical shifts of agricultural land potentials as a result of changing climate.

Various results are also provided as world maps (Plates A–L in this report and Plates 1–70 on the enclosed CD-ROM) and regional tables in the text. Further specific details on the land resource database; suitability and land productivity assessment procedures; and global, regional, and selected country results can be found on the enclosed CD-ROM.

The concluding remarks in Chapter 6 summarize the present status and limitations of the AEZ study and highlight the next phase of development and applications.

The AEZ approach, in combination with socioeconomic modeling, provides an integrated tool for sustainable land-use planning and resource development at the subnational and national level. It is envisaged that the methodology and the results in this first AEZ global assessment will further catalyze regional and country-specific detailed studies.

2

Agro-ecological Zones Methodology

2.1 Introduction

The AEZ methodology uses a land resources inventory to assess all feasible agricultural land-use options for specific management conditions and levels of inputs, and to quantify the expected production of relevant cropping activities. The characterization of land resources includes components of climate, soils, and landform, which are basic for the supply of water, energy, nutrients and physical support to plants. On the basis of this agronomic evaluation, and using available socioeconomic data to formulate constraints, targets, and production options, the spatial resource allocation can be optimized with regard to multiple objectives (Fischer *et al*., 1998).

Recent availability of digital global databases of climatic parameters, topography, soil, terrain, and land cover has allowed for revisions and improvements in calculation procedures. It has also allowed expanding assessments of AEZ crop suitability and land productivity potentials to temperate and boreal environments. This effectively enables global coverage for assessments of agricultural potentials.

The AEZ methodologies and procedures have been extended and newly implemented to make use of these digital geographical databases, and to cope with the specific characteristics of growing periods in the seasonal temperate and boreal climates. These methodological adaptations were necessary for the global application and include: (i) enhancement of the thermal regime analysis with quantification of temperature seasonality, (ii) extension of the moisture regime analysis for frozen soils, snow stocks, and soil-specific water holding capacities, (iii) determination of crop-specific water requirements, deficits, and optimal cropping calendar, and (iv) the application of digital elevation models.

In summary, the following methodological enhancements have been accomplished:

- Selection and definition of additional crop/land utilization types (LUTs) relevant to temperate and boreal environments;
- Extension of the crop/LUT definitions to cover irrigated conditions;
- Expansion of crop ecological adaptability inventory;
- Application of soil-specific moisture regimes, frozen soil conditions, and snow stocks for the calculation of length of growing periods;

- Application of gridded monthly average (period 1961 to 1990) and historical year-by-year climatic resources databases;
- Application of FAO's Digital Soil Map of the World according to the FAO Legend '74 and, where available, application of soil maps classified according to the Revised FAO Legend '90 (currently applied for the Former Soviet Union (FSU), Mongolia, and China);
- Application of the 30 arc-seconds digital elevation model (GTOPO30) to the compilation of a terrain-slope database, and integration of the terrain slopes with soil resources database (refining of slope information of soil maps with the slopes derived from the digital elevation model);
- Enhancement of the assessment procedures for year-by-year crop suitability analysis;
- Expansion of the agro-climatic constraints inventory to cover additional crop/LUTs and temperate and boreal environments;
- Assessment of agro-climatic crop suitability by grid-cell (enabling calculations of biomass, constraint-free yields, agro-climatically attainable yields, crop water requirements and deficits);
- Expansion of land suitability assessment procedures for irrigated crop production.

In its simplest form, the AEZ framework can be described in five basic elements. These are illustrated in *Figure 2.1* and include:

1. *Land utilization types (LUTs)* – Selected agricultural production systems with defined input and management relationships, and crop-specific environmental requirements and adaptability characteristics;
2. *Land resources database* – Geo-referenced climate, soil, and terrain data, combined into a database;
3. *Crop yields and LUT requirements matching* – Procedures for calculating potential yields and for matching crop/LUT environmental requirements with the respective environmental characteristics contained in the land resources database, by land unit and grid-cell;
4. *Assessments of crop suitability and land productivity*, and
5. *Applications for agricultural development planning*.

Over the past 20 years, the term *agro-ecological zones methodology* has become widely used. It has been associated with a wide range of different activities which are often related yet quite different in scope and objectives (FAO/IIASA/UNFPA, 1982; Fischer and Heilig, 1997; Stewart, 1983; Verheye, 1987; UNDP/SSTC/FAO/SLA, 1994). FAO and IIASA use the term to apply to the framework portrayed in *Figure 2.1*.

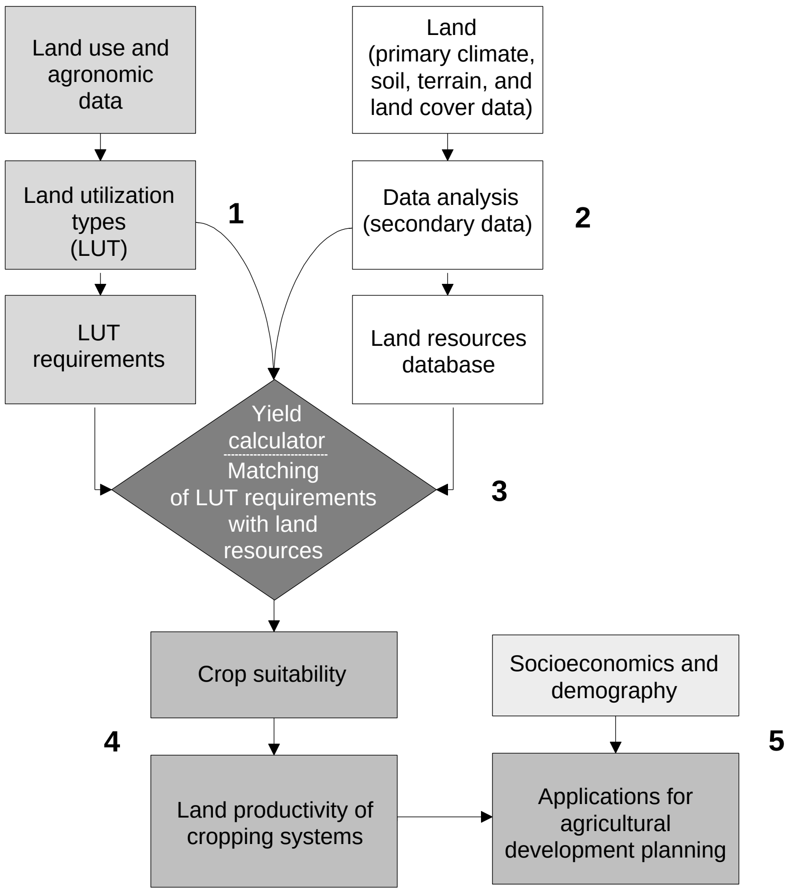

Figure 2.1. Conceptual framework of agro-ecological zones methodology.

First, AEZ provides a standardized framework for characterizing climate, soil, and terrain conditions relevant to agricultural production. The concepts of Length of Growing Period (LGP) and of latitudinal thermal climates have been applied in mapping activities focusing on zoning at various scales, from the subnational to the global level.

Second, AEZ matching procedures are used to identify crop-specific limitations of prevailing climate, soil, and terrain resources, under assumed levels of inputs and management conditions. This part of the AEZ methodology provides maximum potential and agronomically attainable crop yields for basic land resources units (usually grid-cells in the recent digital databases).

Third, AEZ provides the frame for various applications. The previous two sets of activities result in very large databases. The information contained in these data sets form the basis for a number of AEZ applications, such as quantification of land productivity, extents of land with rain-fed or irrigated cultivation potential, estimation of the land's population supporting capacity, and multi-criteria optimization of land resources use and development.

2.2 Overview

Figure 2.2 provides a general overview of the flow and integration of information as implemented in the global agro-ecological zones (GAEZ) assessment. The figure is explained in the following subsections. The subsection numbering corresponds with the numbers used in the figure.

1. **Land utilization types (LUTs):** The first step in an AEZ application is the selection and description of land utilization types to be considered in the study (FAO, 1976a). FAO (1984a) defines LUT as follows: "A Land Utilization Type consists of a set of technical specifications within a socioeconomic setting. As a minimum requirement, both the nature of the produce and the setting must be specified." Attributes specific to particular land utilization types include crop information such as cultivation practices, input requirements, crop calendars, utilization of main produce, crop residues, and by-products. For the global study, the AEZ implementation distinguishes 154 crop, fodder, and pasture LUTs, each at three generically defined levels of inputs and management – termed high, intermediate, and low.

2. **Crop catalog:** The crop catalog database provides a quantified description of LUTs. An example for winter wheat is shown in *Table 2.1*.

   Factors included are crop characteristics such as: length of crop growth cycle, length of individual crop development stages, photosynthetic pathway, crop adaptability group, maximum leaf area index, harvest index, development-stage-specific crop water requirement coefficients, yield reduction factors relating moisture stress and yield loss according to FAO (1979), food content coefficients (energy, protein), extraction/conversion rates, crop by-product/residue coefficients, and commodity aggregation weights. Also included are parameters describing, for both rain-fed and irrigated LUTs, thermal requirements, growing period requirements, and soil and terrain requirements, applicable in tropical, subtropical, temperate, and boreal environments, respectively.

3. **Climate database:** Climatic data are an essential requirement for agro-ecological assessments. In the past, various efforts have been undertaken to develop global climate databases (e.g., see Kineman and Ohrenschall, 1992). The GAEZ study uses a data set that was recently published by the Climate

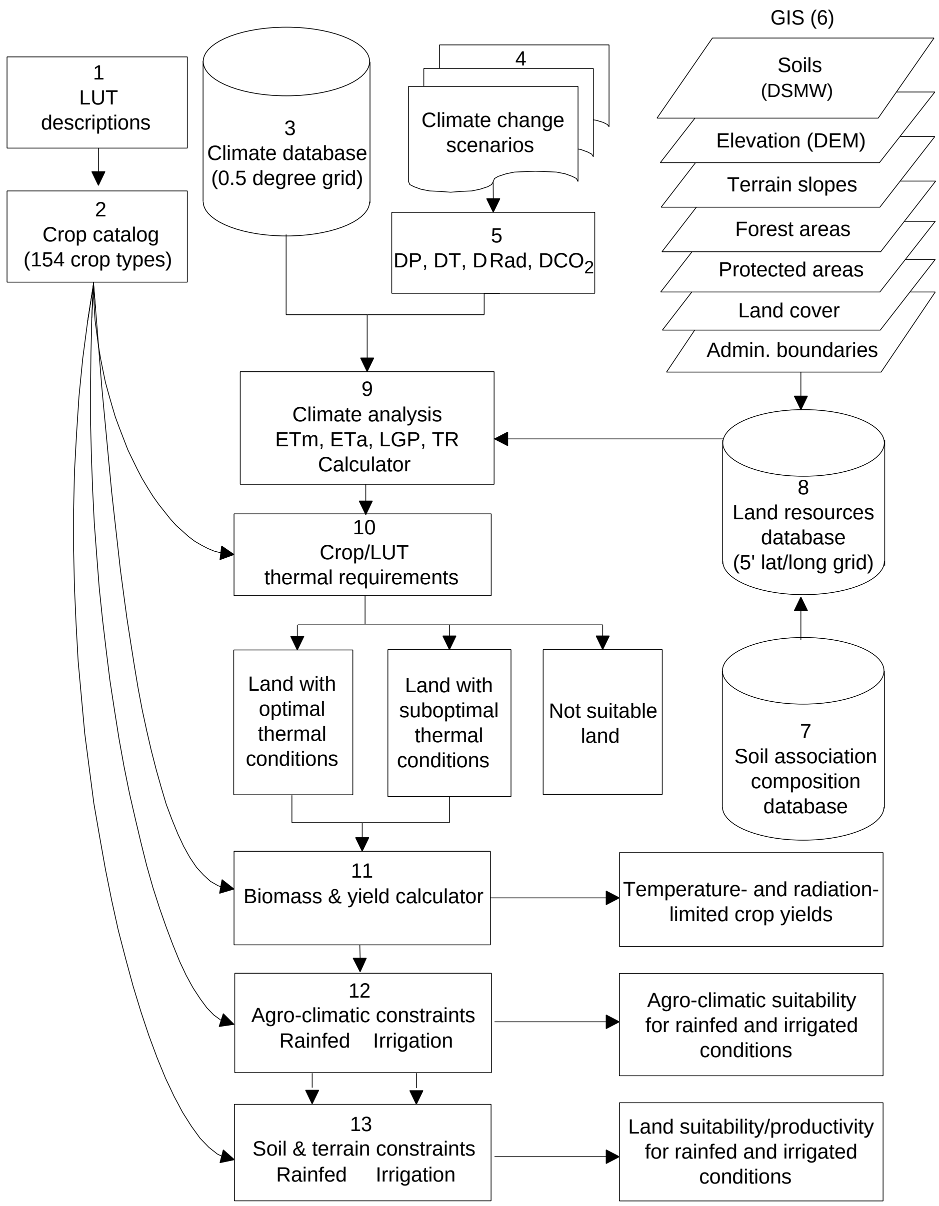

Figure 2.2. Global agro-ecological zones methodology.

Table 2.1. An example of crop parameterization in GAEZ: Winter wheat, high level of inputs.

	Crop characteristics	
Adaptability group		C3/1
Growth cycle		110–130 days
Pre-dormancy period		30 days
Post-dormancy period		90 days
Maximum leaf area index		4.5
Crop stages (%)	Initial	10
	Crop development	30
	Mid-season	35
	Late season	25
Crop water requirement	Initial	0.4
(K_c-factor)	Crop development	0.4–1.1
	Mid-season	1.1
	Late season	1.1–0.4
Moisture-stress-related yield	Initial	0.2
reduction (K_y-factor)	Crop development	0.6
	Mid-season	0.75
	Late season	0.50
	Crop requirements	
Thermal climates		Boreal, temperate, subtropics
Temperature profile		See Chapter 4
Growing period		See Chapter 4
Dormancy		Required
Post-dormancy accumulated temperature (optimal)		> 1300
Post-dormancy accumulated temperature (suboptimal)		> 1200
Sensitivity to soil moisture depletion		Class 3
Soil and terrain conditions		See Chapter 4
	Crop conversion factors	
Harvest index		0.45
Cereal equivalent ratio		1.0
Extraction rate		75%
Energy contents (Kcal/1,000 g)		3,640
Protein contents (g/1,000 g)		110
Crop residue factor (kg dry matter/kg yield)		1.0
Crop residue utilization rate		40%
Crop by-product factor (kg dry matter/kg yield)		0.20
Crop by-product utilization rate		90%

Research Unit (CRU) of the University of East Anglia (New *et al*., 1998). The CRU database covers all the climate parameters required for GAEZ and consists of data sets describing average climate conditions (years 1961–1990) as well as data for individual years from 1901 to 1996. Data are organized in a global 30-minute latitude/longitude grid (720 $\times$ 360 grid-cells). Computations for average climate conditions, and historical year-by-year calculations for the years 1960 to 1996 have been completed in the GAEZ study.[1]

4. **Climate scenarios:** Several climate scenarios based on sensitivity tests and general circulation models (GCM) were selected for use in GAEZ. Outputs from six GCM experiments were obtained through the Data Distribution Center (DDC) of the Intergovernmental Panel on Climate Change (IPCC). They include the following models/scenarios for the periods 2010–2039, 2040–2069, and 2070–2099:

   - *The ECHAM4 model*. This model was developed at the German Climate Research Centre of the Max-Planck Institute for Meteorology in Hamburg, Germany (Oberhuber, 1993; Roeckner *et al*., 1992; Roeckner *et al*., 1996). Model results were taken from the greenhouse gases forcing scenario and from the greenhouse gases plus sulfate Aerosols forcing scenario. For the latter only the 2010–2039 period was available. The scenario results from ECHAM4 are provided at spatial resolution of approximately 2.8 $\times$ 2.8 degrees latitude and longitude.
   - *The CGCM1 model*. This model – the Canadian Global Coupled Model – was developed at the Canadian Centre for Climate Modelling and Analysis. Model results were taken from the greenhouse gases forcing scenario and from the average of “ensemble” simulations (ensemble simulations are based on identical historical and future changes in greenhouse gases, however initiated from different points on the control run). The average “ensemble forcing scenario” was taken for the greenhouse gases plus sulfate Aerosols. The scenario results from CGCM1 are provided at spatial resolutions of 3.75 $\times$ 3.75 degrees (Boer *et al*., 2000; Flato *et al*., 2000).
   - *The HADCM2 model.* This model is based on recent experiments performed at the Hadley Centre for Climate Prediction and Research (Murphy, 1995; Murphy and Mitchell, 1995). Model results were taken from the average of “ensemble” simulations. Outputs were used for, respectively, greenhouse gases only and for greenhouse gases plus sulfate Aerosols. The scenario results from HADCM2 are available at a spatial resolution of 3.75 $\times$ 2.75 degrees.

For use in GAEZ, outputs from the six climate model experiments, available for three time periods and with various spatial resolutions, have been interpolated to 0.5×0.5 degrees.

5. **Scenario-derived climatic parameters:** At minimum, four climatic parameters from the GCM results were used to adjust the baseline climate conditions of each grid-cell. The *difference* (ΔT) in monthly mean maximum and minimum temperatures, between a GCM climate change run and the respective GCM control experiment (representing approximately current base climate), were added respectively to the mean monthly maximum and minimum temperatures of the baseline climate surfaces. Multipliers, i.e., the *ratio* between GCM climate change and control experiment, were used to impose changes in precipitation (ΔP) and incident solar radiation (ΔRad), respectively. When available from a GCM, changes in wind speed and relative humidity were considered as well. Each climate scenario is also characterized by level of atmospheric CO_2 (ΔCO_2) concentrations and assumed changes of crop water-use efficiency. These parameters affect both the estimated reference evapotranspiration as well as the crop biomass estimations.

6. **Land characteristics coverages (GIS):** Soils, elevation, terrain slopes, forest areas, protected areas, land cover, and administrative divisions are kept as individual layers in the GIS and can be combined as needed. Digital soil information for GAEZ was obtained from FAO. The Digital Soil Map of the World (DSMW, version 3.5) provides classification at 5-minute latitude/longitude grid-cells and global coverage of soils according to the FAO Legend '74 (FAO, 1995c).[2] For elevation, the GTOPO30 data set was used (EROS Data Center, 1998). At IIASA, rules based on altitude differences of neighboring grid-cells were applied to compile a terrain-slope distribution database (by FAO DSMW 5-minute grid-cell) in terms of seven average slope range classes.[3] A coverage of protected areas was obtained from the FAO GIS in Rome. Distributions of present land cover for each 5-minute latitude/longitude grid-cell of the DSMW were derived from a Global Land Cover Characteristics (GLCC) database at 30 arc-seconds latitude/longitude (EROS Data Center, 2000).

7. **Soil association composition database:** The composition of the soil associations in terms of percentage occurrence of soil units, soil phases, textures, and terrain-slope classes is stored in the soil association composition database. For the characterization of the soil units in terms of physical and chemical properties, use has been made of (i) the soil unit characteristics database from the FAO DSMW CD-ROM (FAO, 1995c), and (ii) the soil profile database of the World Inventory of Soil Emissions Potential (WISE) (Batjes, 1995). The latter

database provides information on physical and chemical soil attributes for soil units of both the FAO '74 and the FAO '90 classifications (Batjes *et al.*, 1997).

8. **Land resources database (GIS):** The individual GIS layers with their attribute data and distributions at 5-minute latitude/longitude constitute the land resources database. The key components of this database include the FAO DSMW and linked soil association composition table, the 5-minute latitude/longitude slope distribution database, derived from GTOPO30, and a database derived from the US Geological Survey (USGS) GLCC data set, providing distributions in terms of 11 aggregate land-cover classes for each 5-minute grid-cell of the DSMW. The DSMW has been made the reference for constructing a land surface mask, i.e., a binary layer that distinguishes grid-cells as land or sea, respectively. Also, each 5-minute grid-cell is uniquely assigned to an administrative unit, a country, or a disputed area. This might affect summations, in particular for smaller countries.

9. **Climate data analysis (ET_0, ET_a, LGP, and TR calculation):** From the attributes in the climate database, monthly totals of reference evapotranspiration (ET_0) are calculated for each grid-cell according to the Penman–Monteith equation (FAO, 1992b). A water-balance model, comparing moisture supply to crops from precipitation and storage in soils with potential evapotranspiration, provides estimations of actual evapotranspiration (ET_a), and length of growing period (LGP). The LGP calculations also indicate the number and type of growing periods per year, their starting and ending dates, and moisture excess and deficits during the growing periods. Further explanations of the moisture balance calculations are provided in Section 3.1.4; calculation of ET_0 is described in Appendix V on the CD-ROM. Thermal regimes (TR) are quantified for each grid-cell in terms of four kinds of attributes (see also examples in *Table 2.2*), namely: thermal climates, temperature profiles, temperature growing periods (LGP_t), and accumulated temperature (TSUM) calculated for various base temperatures both over an entire year as well as over growing period days. Thermal regimes are further discussed in Section 3.1.3.

10. **Crop/LUT thermal requirements:** Temperature profile requirements, temperature growing period requirements, and temperature sum requirements of LUTs are matched with actual temperature regimes in grid-cells. The temperature profile requirements of crops are formulated on the basis of temperature intervals of 5°, determined separately for seasons with increasing and decreasing temperature trends. These periods are matched with the temperature profiles calculated from temperature data. When the temperature characteristics in a particular grid-cell match, respectively, the temperature profile requirement,

Table 2.2. Climate parameters for Bangkok, Harbin, Manaus, Marseille, Nairobi, and Vienna.

Parameter	Bangkok	Harbin	Manaus	Marseille	Nairobi	Vienna
Mean temperature ($^\circ$C)	28.4	4.1	27.3	13.4	18.3	9.8
Thermal climate^a	1	6	1	3	1	5
Temperature profile	Table 3.3	Table 3.3	Table 3.3	Table 3.3	Table 3.3	Table 3.3
Precipitation (mm)	1,188	524	2,273	749	976	622
ET_0 (mm)	1,641	968	1,481	1,215	1,629	860
ET_a (mm)	1,042	510	1,354	745	932	602
LGP$_{t=0}$ (days)	365	305	365	365	365	318
LGP$_{t=5}$ (days)	365	291	365	365	365	243
LGP$_{t=10}$ (days)	365	274	365	226	365	185
TSUM$_{t=0}$	10,350	3,211	9,950	4,906	6,688	3,625
TSUM$_{t=5}$	10,350	3,143	9,950	4,906	6,688	3,454
TSUM$_{t=10}$	10,350	2,885	9,950	3,922	6,688	3,020
LGP (total) (days)	239	129	365	269	208	243
Number of LGPs	1	2	1	1	2	1
Beginning of LGP 1	day 124	day 175	n.a.	day 262	day 84	day 74
End of LGP 1	day 362	day 291	n.a.	day 165	day 218	day 314
Beginning of LGP 2	n.a.	day 100	n.a.	n.a.	day 306	n.a.
End of LGP 2	n.a.	day 111	n.a.	n.a.	day 13	n.a.
Annual P/ET_0	0.72	0.54	1.53	0.62	0.60	0.72

^{a}1: Tropics, 3: Subtropics winter rainfall, 5: Temperate subcontinental, 6: Temperate continental.

minimum length of temperature growing period, and accumulated temperature requirements, then the crop LUT is considered for cultivation and biomass/yield calculations are performed. A more detailed discussion of crop/LUT thermal requirements is presented in Chapter 4.

11. **Biomass and yield calculation:** The calculation of biomass and crop yield used in GAEZ is based on Kassam (1977) and FAO (1979, 1992a). The *constraint-free crop yields* computed in the biomass module (see Appendix VI on the CD-ROM) reflect yield potentials with regard to temperature and radiation regimes prevailing in the respective grid-cells. Results are geographical distributions of temperature and radiation limited yields of individual crop/LUTs.

12. **Agro-climatic constraints:** Agro-climatic constraints have their origin primarily due to climate, and cause direct or indirect losses in the yield and quality of produce. Yield losses of a rain-fed crop due to agro-climatic constraints are influenced by the following conditions:

    - The variability and degree of water-stress during the growing period;
    - The yield-quality reducing factors of pests, diseases, and weeds;

- The climatic factors, operating directly or indirectly, that reduce yield and quality of produce mainly through their effects on yield components and yield formation;
- The climatic factors which affect the efficiency of farming operations and costs of production;
- The risk of occurrence of late and early frost.

The agro-climatic constraints in GAEZ are specified by means of adjustment factors linked to the standardized evaluation of the temperature and moisture regimes in each grid-cell, i.e., they are essentially formulated based on length of thermal growing period (LGP_t) and length of moisture growing period (LGP). In addition, the factors depend on crop type and level of inputs/management.

13. **Soil and terrain constraints:** The agro-edaphic suitability assessment is based on the comparison of edaphic requirements of rain-fed and irrigated crop/LUTs and prevailing soil and terrain conditions. The edaphic assessment also reflects constraints imposed by landform and other features that do not directly form a part of the soil but may have a significant influence on the use that can be made of the soil. Distinction is made between *internal* soil requirements of crop/LUTs, such as soil temperature regime, soil moisture regime, soil fertility, effective soil depth for root development, and other physical and chemical soil properties, and *external* requirements related to soil slope, occurrence of flooding and soil accessibility. The results of matching the crop/LUT-specific edaphic requirements to the soil and terrain attributes of individual grid-cells, in combination with calculated potential biomass and agro-climatically attainable yields, provides a suitability classification for each rain-fed and irrigated crop/LUT, respectively, at high, intermediate, and low levels of input circumstances. To safeguard production so that it is achievable on a long-term basis, two further considerations are applied in the assessment:

- Fallow requirements are imposed to enable maintenance of soil fertility and structure and to counteract soil degradation caused by cultivation. Fallow requirements vary by environmental conditions, crop, and level of inputs/management (FAO/IIASA, 1991). Principles of formulating fallow requirement factors in GAEZ are discussed in Section 4.6 and Appendix XII.
- The terrain-slope suitability classification is concerned not only with workability and accessibility of the land, but also with the prevention of intolerable levels of topsoil erosion and fertility loss. Depending on prevailing rainfall aggressivity, level of inputs/management, and crop/LUT, upper limits have been set to slope gradients considered suitable for cultivation.

Notes

[1] For average climate conditions, results were also obtained with the CLIMATE database of Cramer and Leemans (an update and extension of Leemans and Cramer, 1991). Note also, that these climate data sets are not available from FAO or IIASA, but can be obtained from the respective authors.

[2] It should be noted that GAEZ is also ready to operate with updates of the DSMW. For instance, for the countries of the FSU, Mongolia, and China, recently updated soil maps in digital format provide classifications in terms of the Revised FAO Legend '90 (Stolbovoi, 1998; FAO/IIASA, 1999).

[3] Due to the size of grid-cells, algorithms calculating slope angles among neighboring 30 arc-seconds grid-cells of GTOPO30 give unrealistic slope distributions that overestimate extents of terrain with flat and undulating slopes.

3

Land Resources

3.1 Introduction

The AEZ methodology for land productivity assessments follows an environmental approach and provides a framework for establishing a spatial inventory and database of land resources and crop production potentials. This land resources inventory is used to assess, at specified management conditions and levels of inputs, how suitable crops/LUTs are in relation to both rain-fed and irrigated conditions, and to quantify the expected production of cropping activities relevant in the specific agro-ecological context. The characterization of land resources includes components of climate, soils, landform, and current land cover.

Inherent in the methodology is the generation of a climatic inventory to predict agro-climatic yield potentials of crops. The GAEZ study uses a recent global climatic data set compiled by the CRU at the University of East Anglia (New *et al*., 1998). The database offers a spatial resolution of 30-minute latitude/longitude and contains climate averages for the period 1961–1990 as well as year-by-year data of the period 1901–1996. These are used to characterize each half-degree grid-cell in terms of applicable thermal climates, temperature profiles, accumulated temperature sums, length of growing periods, moisture deficits, etc.

Adequate agricultural exploitation of the climatic potentials and maintenance of land productivity largely depend on soil fertility and the management of soils on an ecologically sustained basis. Hence, the climatic inventory was superimposed on FAO's Digital Soil Map of the World (DSMW). The DSMW is derived from the FAO/UNESCO Soil Map of the World at a scale of 1:5 million and presents soil associations in grid-cells of 5-minute latitude/longitude. It forms the basis of soil information in GAEZ. The composition of soil associations is described in terms of percentage occurrence of soil units, soil phases, and textures. Therefore, each 5-minute grid-cell is considered as consisting of several land units.

Terrain slopes were derived from the GTOPO30 database developed at the USGS EROS Data Center, providing digital elevation information in a regular grid of 30 arc-seconds latitude/longitude. At IIASA, rules based on altitude differences of neighboring grid-cells were applied to compile a terrain-slope distribution database (for each 5-minute grid-cell of FAO's DSMW) in terms of seven average slope range classes.

The individual GIS layers with attribute data and distributions at 5-minute latitude/longitude constitute the land resources database. The key components of this database include:

- The FAO DSMW and linked soil association composition table,
- The slope distribution database derived from GTOPO30, and
- An ecosystem database derived from the USGS 30 arc-seconds seasonal land cover data set, providing distributions in terms of 12 aggregate land-cover classes for each 5-minute grid-cell.

The DSMW has been made the reference for constructing a land surface mask, i.e., a binary layer that distinguishes grid-cells as land or sea, respectively. Also, each 5-minute grid-cell is uniquely assigned to an administrative unit (a country or region).

3.2 Climate Resources

3.2.1 Introduction

Living organisms require heat, light, and water in varying amounts. Their distribution, in space and time, is governed by these climatic elements. In the AEZ approach, as in any bio-geographic inventory, temperature, water, and solar radiation are the key climatic parameters. These parameters condition rates of net photosynthesis, allowing plants to accumulate dry matter and to accomplish the successive plant development stages. Data on climatic requirements of crop growth, development, and yield formation are the basis for the compilation of the AEZ climatic inventory. Also, crops need to be characterized for their thermal and moisture adaptability. Prevailing temperatures determine crop performance when moisture conditions are met. Similarly, when temperature requirements are met, the growth of a crop is dependent on how well its growth cycle fits within the period when water is available. The latter has led to the concept of *length of growing period* (LGP). LGP allows an environmental characterization particularly relevant to agricultural assessments. It is defined as the number of days when both water availability and prevailing temperatures permit crop growth. Depending on its length, the LGP may allow for no crops or for only one crop per year (e.g., in arid or dry semi-arid tropics), or it may allow the growth of a sequence of crops within one year (e.g., in humid tropics or subtropics). In the GAEZ, LGP is used to determine periods within a year available for rain-fed crop production, and to select applicable agro-climatic constraints.

Table 3.1. Attributes in the CRU climate databases.

Monthly variables (normals 1961–1990)	Monthly variables (historical data 1901–1996)
Precipitation[a]	Precipitation
Wet days frequency[a]	Wet days frequency
Mean temperature[a]	Mean temperature
Diurnal temperature range[a]	Diurnal temperature range
Vapor pressure[a]	Vapor pressure
Cloud cover	
Sunshine (n/N)[a]	
Ground-frost frequency	
Windspeed[a]	

[a] Mean monthly climate attributes.

3.2.2 Climate data

The GAEZ study uses a recent global climate data set, referred to herein as the "CRU" climate database (see Section 3.1). This database comprises a suite of nine climatic variables (see *Table 3.1*) interpolated from observed station data to a 30-minute latitude/longitude grid. Each data set contains 720 $\times$ 360 grid-cells (only grid-cells over land are provided). *Table 3.1* presents the climate parameters held in the CRU database by grid-cell.

The year-by-year historical databases, along with the 1961–1990 average climate database, have been used to quantify growing period variability and to estimate for each grid-cell by crop/LUT the variability of agro-climatically attainable crop yields. Average annual rainfall and estimated reference evapotranspiration, calculated according to Penman–Monteith, have been compared with average data from climate stations of the FAOCLIM database (FAO, 1995b). Their correlation is shown in *Figure 3.1*. There are several important reasons why station data and values obtained from grid-cells can (and should) be different: (i) the observation period of stations and the 1961–1990 climate normals of the CRU grid can be quite different both in time period and number of years; (ii) the grid values represent average conditions for a 0.5 degree latitude/longitude cell size; in complex terrain or for areas with strong moisture gradients, this heterogeneity can lead to large discrepancies.

Maps of annual rainfall and reference evapotranspiration totals are reproduced as Plate 1: Average annual precipitation and Plate 2: Average annual reference evapotranspiration (according to Penman–Monteith). Both plates are found on the accompanying CD-ROM.

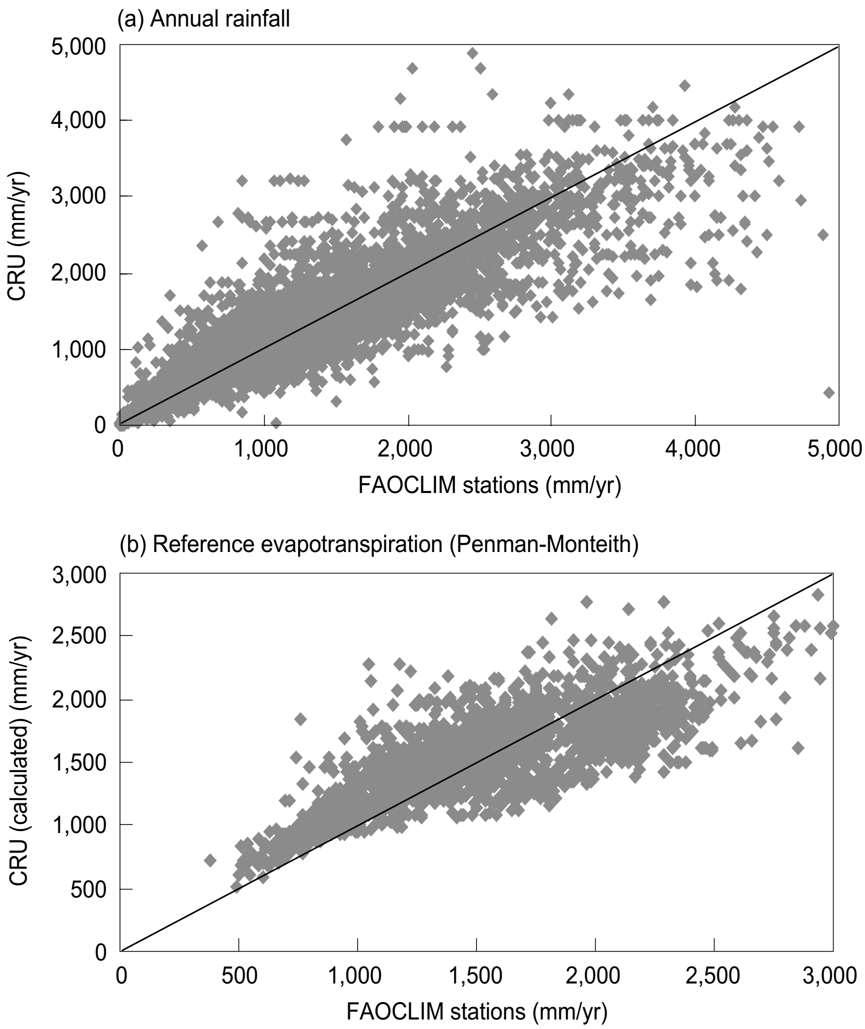

Figure 3.1. Scattergram of (a) annual rainfall and (b) reference evapotranspiration (Penman–Monteith), between grid-cell data from the CRU 1961–1990 climate normals database and average station data of the FAOCLIM database.

3.2.3 Thermal regimes

Photosynthesis produces the assimilates that plants use for growth and development. Temperature and radiation influence the rate of photosynthesis. However, plants also have an obligatory development in time, which must be met if the photosynthetic assimilates are to be converted into economically useful yields of satisfactory quantity and quality. Temperature, and day-length in the case of photosensitive crops, influence the developmental sequence of crop growth in relation to crop phenology. Therefore, the temperature regime and photo-periodicity govern the selection of the crops that can be cultivated. In some cases, temperature may determine whether a particular development process will be initiated or not (e.g., chilling requirements for initiation of flower buds). Low temperatures can also delay flowering and fruit setting. For photosensitive cultivars, day-length plays an important role in determining the time of flowering. For instance, many soybean varieties will not flower under equatorial conditions. Deepwater rice flowers after the day has shortened to a certain number of day-light hours, which coincides in Southeast Asia with the end of the rainy season.

The evolutionary changes that have occurred in the biochemical and physical characteristics of photosynthesis have resulted in a large variation between crops in both their optimum temperature requirements and the responses of photosynthesis to changes in temperature and radiation. These responses depend on the nature of the photosynthetic pathway. In general, the C_3 pathway of assimilation[1] is adapted to operate at optimum rates under lower temperature conditions than the C_4 assimilation pathway.[2] However, breeding and selection (both natural and under human influence) have changed temperature responses of photosynthesis in some C_3 and C_4 species. It is therefore possible to make a division of the major food crops according to their assimilation pathway and corresponding temperature requirements. Four groups have been recognized in AEZ:

Group I C_3 species adapted to lower temperatures (e.g., wheat, potatoes);

Group II C_3 species adapted to higher temperatures (e.g., soybean, rice, cassava);

Group III C_4 species adapted to higher temperatures (e.g., millet, sorghum, maize, sugarcane);

Group IV C_4 species adapted to lower temperatures (e.g., sorghum, maize).

Figure 3.2 shows for each crop group examples of the relationship between the rate of photosynthesis at optimum temperature and photosynthetically active radiation. *Figure 3.3* illustrates for each group of crops the typical (inverted) u-shaped effect of temperature on the leaf photosynthesis.

To cater for differences in thermal requirements of crops, an adequate characterization of the temperature regimes is required, applicable to a wide range of locations. With the improved spatial availability of climate attributes and the extension of GAEZ to temperate and boreal seasonal climates, the characterization of the temperature regimes in the current approach consists of four parts, namely:

1. Thermal climates, representing major latitudinal climatic zones;

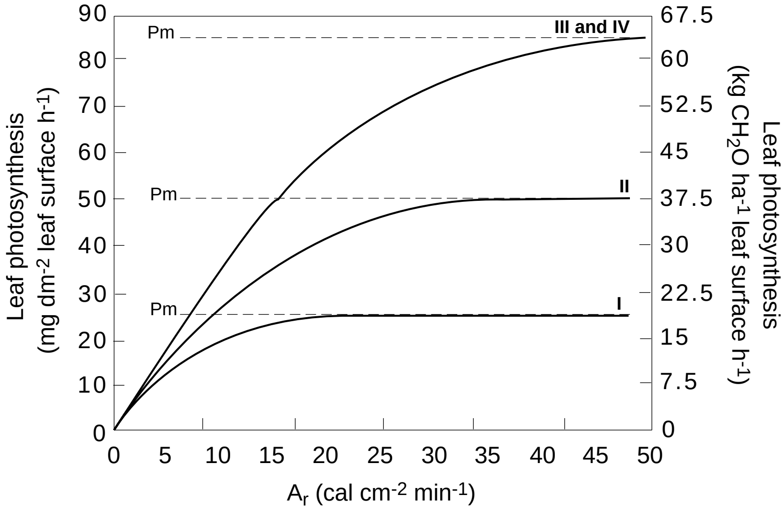

Figure 3.2. Relationship between leaf photosynthesis rate at optimum temperature and photosynthetically active radiation for crop groups I, II, III, and IV (FAO, 1978–1981a).

Note: The leaf photosynthesis values presented in *Figure 3.2* and *3.3* reflect base period (1961–1990) levels of atmospheric carbon dioxide concentrations.

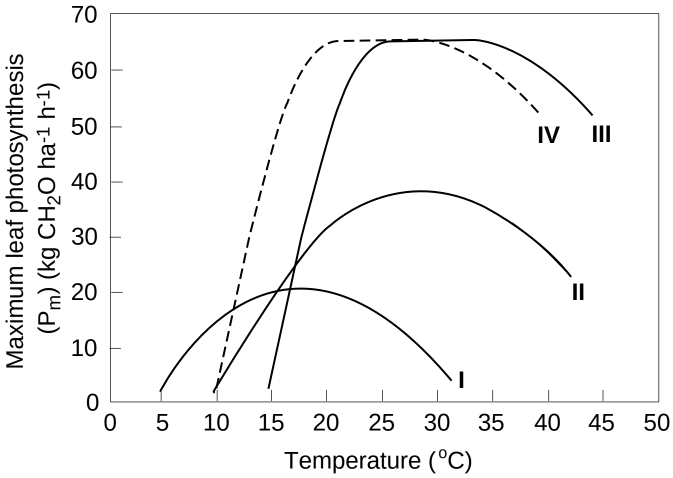

Figure 3.3. Examples of relationships between maximum leaf photosynthesis rate (P_m) and temperature for crop groups I, II, III, and IV (FAO, 1978–1981a).

Table 3.2. Thermal climate classification.

Tropics All months with monthly mean temperatures, corrected to sea level, above 18°C	
Subtropics One or more months with monthly mean temperatures, corrected to sea level, below 18°C but above 5°C	*Subtropics summer rainfall* Northern hemisphere: rainfall in April–September ≥ rainfall in October–March Southern hemisphere: rainfall in October–March ≥ rainfall in April–September
	Subtropics winter rainfall Northern hemisphere: rainfall in October–March ≥ rainfall in September Southern hemisphere: rainfall in April–September ≥ rainfall in October–March
Temperate At least one month with monthly mean temperatures, corrected to sea level, below 5°C and four or more months above 10°C	*Oceanic temperate* Seasonality less than 20°C[a]
	Subcontinental temperate Seasonality 20–35°C[a]
	Continental temperate Seasonality more than 35°C[a]
Boreal At least one month with monthly mean temperatures, corrected to sea level, below 5°C and more than one but less than four months above 10°C	*Oceanic boreal* Seasonality less than 20°C[a]
	Subcontinental boreal Seasonality 20–35°C[a]
	Continental boreal Seasonality more than 35°C[a]
Polar/Arctic All months with monthly mean temperatures, corrected to sea level, below 10°C	

[a] Seasonality refers to the difference in mean temperature of the warmest and coldest month, respectively.

2. Temperature profiles, providing quantification of temperature seasonality;
3. Temperature growing periods (LGP_t), representing the periods during which average daily temperatures exceed specified minimum levels; and
4. Accumulated temperature (temperature sums), calculated for various base temperatures.

Thermal Climates

The thermal climates are obtained through classifying of monthly temperatures corrected to sea level (with an assumed lapse rate: 0.55°C/100 m). For the classification of latitudinal thermal climates, the AEZ major climatic divisions of tropics, subtropics with summer rainfall, subtropics with winter rainfall, and temperate (FAO, 1978–1981a) have been expanded with boreal and polar/arctic divisions. The temperate and boreal belts have been further subdivided according to continentality into three classes, namely: oceanic, subcontinental, and continental. *Table 3.2* presents the thermal climate classification used in the GAEZ study. The geographic

Table 3.3. Examples of average temperature profiles for Bangkok, Harbin, Manaus, Marseille, Nairobi, and Vienna.

Temperature		Temperature periods (days)					
intervals (°C)		Bangkok	Harbin	Manaus	Marseille	Nairobi	Vienna
A9	< -5	0	56	0	0	0	0
A8	–5–0	0	14	0	0	0	23
A7	0–5	0	13	0	0	0	36
A6	5–10	0	17	0	79	0	32
A5	10–15	0	22	0	43	0	33
A4	15–20	0	27	0	40	227	74
A3	20–25	0	38	0	33	9	0
A2	25–30	95	0	258	0	0	0
A1	> 30	21	0	0	0	0	0
B1	> 30	25	0	0	0	0	0
B2	30–25	224	0	107	0	0	0
B3	25–20	0	32	0	43	8	0
B4	20–15	0	20	0	38	121	49
B5	15–10	0	19	0	29	0	29
B6	10–5	0	17	0	60	0	26
B7	5–0	0	14	0	0	0	39
B8	0–5	0	13	0	0	0	24
B9	< -5	0	63	0	0	0	0

distribution of the thermal climates is presented in Plate A in this report (Plate 3 on CD-ROM).

Temperature Profiles

The quantification of temperature seasonality looks at year-round temperature regimes. They are expressed in number of days falling into pre-defined temperature intervals. These intervals consist of 5°C steps, subdivided, respectively, into periods with increasing and decreasing temperatures. “A” classes are used for increasing temperatures and “B” classes for decreasing temperatures. A complete account of time periods of individual temperature intervals provides a year-round *temperature profile*. These profiles have been calculated for each grid-cell; examples are shown in *Table 3.3*.

Temperature Growing Periods and Temperature Sums

In addition to thermal climates and temperature profiles, temperature growing periods (LGP_t) have been inventoried. For instance $LGP_{t=5}$ (of 5°C), i.e., the number of days when mean daily temperature exceeds 5°C, represents the period with temperatures suitable for crop growth. Similarly, $LGP_{t=10}$ (of 10°C) approximates the frost-free period (see Plates 4 and 5, CD-ROM). Lengths, beginning dates, and ends of such periods are calculated for each grid-cell and are stored in the attribute database. Also, for various base temperatures, accumulated temperatures have been calculated for each grid-cell. For instance, the accumulated temperature on days with mean daily temperature above 0°C is shown on Plate 6 (CD-ROM).

3.2.4 Moisture regimes

A general characterization of moisture conditions is achieved through the concept of *length of growing period* (LGP), i.e., the period during the year when both moisture availability and temperature are conducive to crop growth. Thus, in a formal sense, LGP refers to the number of days within $\text{LGP}_{t=5}$ when moisture conditions are considered adequate.

Under rain-fed conditions within $\text{LGP}_{t=5}$, the beginning of the LGP is linked to the start of the rainy season. Farmers' cropping strategies are undoubtedly influenced by the variability they have experienced in the onset of the rainy season. In general, they will plant or dry-seed their crop when certain amounts of rainfall have accumulated and sufficiently moistened the topsoil. The start of the growing period is therefore dependent on the amount and frequency distribution of early rains. The reliability of precipitation of these early rains increases considerably once the monthly precipitation equals or exceeds half the potential evapotranspiration (FAO, 1978–1981a). Furthermore, the amount of moisture required to sustain growth of germinating crops is well below evapotranspiration demand of crops at maximum canopy cover. For establishing crops, 0.4–0.5 times the level of reference evapotranspiration is considered sufficient to meet water requirements of dryland crops (FAO 1978–1981a; 1979; 1992a). Details of the calculation of potential evapotranspiration are presented in Appendix V (CD-ROM).

The growing period for most crops continues beyond the rainy season and, to a greater or lesser extent, crops mature on moisture stored in the soil profile. However, the amount of soil moisture stored in the soil profile, and available to a crop, varies, e.g., with depth of the soil profile, the soil's physical characteristics, and the rooting pattern of the crop. Depletion of soil moisture reserves causes the actual evapotranspiration to fall short of the potential rate. Soil moisture storage capacity of soils ($S_{\max}$) depends on the soil's physical and chemical characteristics, but above all on effective soil depth or volume. For the soil units of the Legend of the Soil Map of the World (FAO/UNESCO, 1974), FAO has developed procedures for the estimation of $S_{\max}$ (FAO, 1995c). The classes are estimated for individual FAO soil units and are presented in Appendix XIII (CD-ROM). Occurrence of soil depth/volume limiting soil phases is accounted for as summarized in *Table 3.4*. For each mapping unit (and each grid-cell) the composition in terms of soil units and the occurrence of soil depth/volume limiting soil phases is known from the DSMW. The relevant values for individual soil units in a grid-cell were used to set limits to

Table 3.4. Soil moisture storage capacity classes (all columns in mm) for soil depth/volume limiting soil phases.

Soil unit storage capacity	Soils with lithic phase	Soils with petroferric and duripan phases (Revised Legend ‘90) or petrocalcic, petrogypsic, petroferric, and duripan phases (Legend ‘74)	Soils with skeletic and rudic phases (Revised Legend ‘90) or petric and stony phases (Legend ‘74)
150	50	115/50	75
125	40	90/40	65
100	35	75/35	50
75	25	55/25	40
50	15	35/15	25
15	n.a.	n.a.	n.a.

available soil moisture, enabling calculation of possible extension of the growing period beyond the end of the rainy season by soil unit, soil texture class, and soil phase.

In addition to taking into account soil-specific $S_{\max}$ values, a number of further modifications in the growing period analysis were introduced. The new elements in the water-balance calculations mainly relate to three types of enhancements:

(i) temperature/moisture interactions which are of special relevance in temperate and boreal thermal climates;
(ii) standardization of the water-balance calculations by prior conversion of monthly climate variables to pseudo-daily data (using quadratic spline functions), and
(iii) enabling ET_0 and water-balance calculations for each 0.5-degree grid-cell.

More specifically the main changes are the following:

A For the calculation of reference evapotranspiration, the modified Penman equation used in earlier assessments has been replaced by the Penman–Monteith equation (FAO, 1992b).

B Monthly climate parameters are converted to daily data by means of spline interpolations, ensuring consistency of daily levels with monthly means or totals. For each grid-cell, this results in pseudo-daily values for all parameters relevant in the calculation of reference evapotranspiration and water-balance. [This conversion of monthly (or decade) data to daily values simplifies the calculation of soil moisture balances and the determination of length of growing period and growing period characteristics. Note that these pseudo-daily values should not be applied in instances where actual daily weather data are required. However, it means that the current algorithms are applicable with minor modifications when daily data are available.]

From these series a daily *water-balance*, W, and *actual evapotranspiration*, ET_a, is calculated according to FAO (1979), as follows:

$$W_{j+1} = \min(W_j + P_j - ET_{a_j},\ dS_{\max}) \tag{3.1}$$

$$ET_{a_j} = \begin{cases} ET_{0_j} & \text{if } W_j + P_j \geq S_{\max} \cdot d \cdot (1-p) \\ \rho ET_{0_j} & \text{else} \end{cases} \tag{3.2}$$

then

$$\rho = \frac{ET_{a_j}}{ET_{0_j}} = \frac{W_0 + P_0}{S_{\max} \cdot d \cdot (1-p)} \tag{3.3}$$

where j is the number of day in year; $S_{\max}$ is the available soil moisture holding capacity (mm/m); d is the rooting depth (m); p is the soil water depletion fraction below which $ET_a < ET_0$; and ρ is the actual evapotranspiration proportionality factor.

$S_{\max}$ and d are defined by the respective values of the soil units in individual grid-cells. The beginning of a growing period is reached when three basic conditions are met: (i) average daily temperature is above 5°C, (ii) actual evapotranspiration (ET_a) exceeds a specified fraction of the estimated reference evapotranspiration, i.e.,

$$ET_{a_j} \geq \alpha ET_{0_j}, \quad \alpha = 0.4 - 0.5 \tag{3.4}$$

[in the current calculations of GAEZ the value of $\alpha = 0.5$ was used], and (iii) sufficient moisture has been accumulated in the soil profile for establishing crops. However, the start of a growing period may be delayed because of excessive wetness due to snowmelt (see *Table 3.5*), especially in flat terrain with poorly drained, medium- to fine-textured soils, e.g., as found in Western Siberia. This might result in saturated soil conditions with low bearing capacities presenting problems for timely seeding/planting. It also will severely affect the oxygen supply to the roots of the hibernating crops.

Depending on the amount of excess moisture, the following assumptions were adopted for the delay of the effective start of a growing period:

A growing period ends when soil moisture supply becomes insufficient or temperature becomes limiting, i.e., on the day when first

$$ET_{a_j} < \beta ET_{0_j}, \quad \beta = 0.4 - 0.5\ , \tag{3.5}$$

Table 3.5. Delay of the growing period start due to excess wetness.

Excess moisture from snowmelt (mm)	Excess moisture at start of $\mathrm{LGP}_{t=5}$ (mm)		Delay of start of growing period to due excess wetness (days)	
	Very poorly drained soils	Poorly/imperfectly drained soils	Very poorly drained soils	Poorly/imperfectly drained soils
40	0	0	0	0
80	20	0	5	0
120	60	30	15	10
180	120	90	30	20
240	180	150	45	30

Note: Drainage classes are according to the FAO Guidelines for Soil Description (FAO, 1990).

or when average daily temperature falls below 5°C. In this way, all the growing periods within a year are fully determined with starting and ending dates, length in number of days, and reference ET_a values. Where applicable, the procedure also records the dates and length of a dormancy period (see below) and of any humid period during a growing period, defined as days when rainfall exceeds reference evapotranspiration, i.e., with $P > ET_0$.

C The water-balance calculation detects and handles specific conditions during cold-breaks or dormancy:

- Frozen topsoil: $T_{\text{mean}} < 0°\text{C}$, then $(ET_a = 0)$,
- Leaf area index (LAI) development expressed as transpiration gradients, after start of growing period or restart after dormancy period.

D The calculation procedures include accumulation of snow stocks and the time periods required to melt snow stocks. Two temperature thresholds control the calculations. When maximum daily temperature falls below a defined limit, then any precipitation occurring is assumed to be in the form of snow and is accumulated as snow stock. During such periods, the sublimation of the snow stock is accounted for. The sublimation rate is a model variable and is set at 0.2. When average daily temperature exceeds the freezing point, melting of snow stocks is modeled by a linear relationship in proportion to maximum daily temperature exceeding a defined threshold (model variables for snow melt are set at 5.5 mm/day/°C, when $T_{\max} > 0°\text{C}$).

E Discontinuous growing periods with a dormancy period have been separated from those with a cold-break on the basis of temperature limits (T_h) for survival of hibernating crops. In defining respective limits, the impact of the depth of snow cover (S_d) on T_h has been accounted for as follows, defining a threshold in the range between –8 and –22°C:

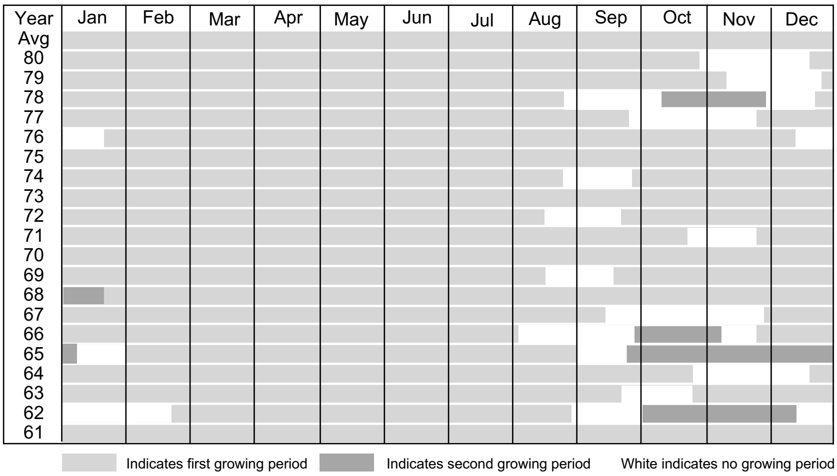

Figure 3.4. Comparison of LGP calculations for average and year-by-year rainfall, Gan Zhou, China.

$$T_h = \begin{cases} -8 - 0.11 \cdot S_d & S_d \leq 127 \text{ cm} \\ -22 & S_d > 127 \text{ cm} . \end{cases} \tag{3.6}$$

An upper limit to the length of the dormancy period can be set. When the duration of the dormancy period exceeds this maximum, the dormancy period is treated as being a cold-break. In the present calculations, the maximum duration of the dormancy period has been set, as a model variable, at 200 days.

F The procedures allow calculation of growing periods for individual years by using the water balance time-series of monthly rainfall. This provides a quantification of year to year variability of the moisture regime. *Figure 3.4* presents, for Gan Zhou, in Jiangxi province in China, the results of LGP analysis with averaged monthly rainfall data of 1961–1980 (shown as average [Avg]) as compared with monthly data of individual years. The figure highlights the importance of assessing year-by-year conditions rather than using results derived from average climate data. Average climate data (see top line of *Figure 3.4*) obscure the fact that there are periods within individual years when there is no growing period. While the calculations based on averaged climate conditions result in a year-round LGP, i.e., 365 days, the individual year results fall in between 260 and 365 days, with an average of 326 days.

Plate B in this report (Plate 7 on CD-ROM) shows a map of average total length of growing periods (1961–1990). For presentation, the results for each grid-cell were grouped in 30-day interval classes. Plate 8 (CD-ROM) shows a map with dominantly mono-modal and bi-modal growing period patterns, respectively.

3.3 Soil and Terrain Resources

3.3.1 Soil information

The source of soil information used in GAEZ is primarily the DSMW, the digital version of the FAO/UNESCO Soil Map of the World (FAO, 1995c). It provides classification of soils according to the FAO/UNESCO '74 Legend (FAO/UNESCO, 1974).

For an increasing number of countries in Africa, South America, and Asia the original Soil Map of the World has been or is being updated according to the Revised FAO Legend '90 (FAO/UNESCO/ISRIC, 1990). The available information concerns the updated soil maps for the FSU, Mongolia, and China, referred to as Soil and Terrain Database for North and Central Eurasia (FAO/IIASA, 1999), which were finalized under the Land Use Change Project (LUC) of IIASA in close collaboration with FAO. The map covering the territory of the FSU (i.e., Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldavia, Russian Federation, Tajikistan, Turkmenistan, Ukraine) and Mongolia was compiled at 1:5M scale by Dokuchaev Soil Institute in Moscow (Stolbovoi, 1998). The map covering China at 1:4M scale was compiled by the Institute of Soil Science, Academia Sinica, in Nanjing (FAO/CAS, 1995). Both sets of digital soils information (FAO, 1995c; and FAO/IIASA, 1999) were used for the development of AEZ applications.

The digital soil information constitutes part of the land resources database and is kept together with other geographic information (i.e., elevation, terrain slopes, distance to coast, protected areas, land cover, and administrative divisions). Additional information – specifying the composition of the soil associations in terms of percentage occurrence of soil units, textures, terrain-slope classes, and soil phases – is kept in a soil association composition database. The soil units in the FAO Legends are defined in terms of measurable and observable properties of the soil itself. Many of the properties are directly relevant to agricultural production potential.

Quantification of soil unit characteristics in terms of physical and chemical properties was obtained from: (i) the DSMW CD-ROM for the soil units of FAO/UNESCO 1974 Legend (FAO, 1995c), and (ii) the World Inventory of Soil Emissions Potential (WISE) database (Batjes, 1995). The WISE database contains a wide range of soil attributes for more than 4,000 soil profiles. The International Soil Reference and Information Centre (ISRIC), with assistance from the Land and Water Development Division of FAO and the LUC project of IIASA, has developed procedures for the extraction of relevant soil attributes by soil unit from this WISE soil profile database (Batjes *et al.*, 1997). The individual profiles were classified by ISRIC for both the FAO Legend '74 and the Revised FAO Legend '90. This work facilitates linkage with the FAO/UNESCO Digital Soil Map of the World and the digital soil maps of the FSU, Mongolia, and China.

3.3.2 Terrain slopes

Two sources of geo-referenced terrain slopes were available for use in the GAEZ assessment: (i) terrain slopes indicated in the mapping unit expansion tables of the respective soil maps, and (ii) terrain slopes derived from GTOPO30 data (EROS Data Center, 1998). The latter terrain-slope database was established at IIASA using a rule-based algorithm to calculate slope distributions. They are calculated in terms of seven slope classes per 5-minute grid-cell of the DSMW soil data, based on neighborhood relationships among grid-cells in the 30 arc-seconds GTOPO30 database (see Appendix II on CD-ROM).

Terrain slopes indicated in the DSMW distinguish three broad slope classes as follows:

Class a: *level to undulating*, dominant slopes ranging between 0% and 8%.

Class b: *rolling to hilly*, dominant slopes ranging between 8% and 30%.

Class c: *steeply dissected to mountainous*, dominant slopes more than 30%.

The terrain slopes of the DSMW apply to the dominant soil unit of a soil association mapping unit. Where two slopes are indicated for a mapping unit (i.e., a/b or b/c), they apply each to 50% of the extent of the dominant soil unit. For all associated and included soils, default slope classes are assigned to the individual soil units of FAO ‘74 according to FAO (1978–1981a):

Default slope class	Soil units in FAO ‘74
a	Fluvisols, Gleysols, Histosols, Planosols, Solonchaks, Solonetz, and Vertisols
a/b	Podzols, Yermosols, Xerosols, Kastanozems, Chernozems, Phaeozems, Greyzems, Luvisols, Podzoluvisols, Ferralsols, and Arenosols
b	Regosols, Rendzinas, Cambisols, Acrisols, and Nitosols
b/c	Andosols, Rankers, and Lithosols

The above procedure was also adapted for application to the Revised FAO Legend ‘90:

Default slope class	Soil units in FAO ‘90
a	Fluvisols, Gleysols, Histosols, Planosols, Solonchaks, Solonetz, and Vertisols
a/b	Arenosols, Anthrosols, Chernozems, Ferralsols, Greyzems, Gypsisols, Kastanozems, Luvisols, Lixisols, Podzoluvisols, Phaeozems, Plinthosols, and Podzols
b	Acrisols, Alisols, Calcisols, Cambisols, Nitosols, and Regosols
b/c	Andosols and Lepthosols

The slope classes of the DSMW are very broad and do not reflect the information contained in recent digital data sets. Hence, the above broad slope classes have been refined on the basis of knowledge about soil unit-slope relationships and information derived from GTOPO30. Slopes derived from the 30 arc-seconds digital elevation model (DEM) were allocated to soil units occurring within individual soil associations. This allocation involved five steps:

(i) Determine slope classes for each 30 arc-seconds grid-cell of GTOPO30. Results are grouped into the following seven classes: 0–2%, 2–5%, 5–8%, 8–16%, 16–30%, 30–45%, and $> 45\%$;
(ii) Aggregate the results, respectively, into 5-minute latitude/longitude DSMW grid-cells, and into individual soil association map units, deriving a slope class distribution for each grid-cell and soil association map unit;
(iii) Define “priority” classes of soil unit/slope relationships;
(iv) Establish, for each soil association, consistent rankings of slopes/soil units;
(v) Allocate individual soil units within a particular soil association map unit to 5-minute grid-cells of DSMW, according to calculated slope distributions.

Details of the above steps are given in the Appendix II (CD-ROM). Plate C (this report) presents a map of median terrain slopes derived from GTOPO30.

3.4 Soil and Terrain Constraints

In addition to the crop-specific suitability assessments (see Chapter 4), the land resources inventory allows characterization of various regions according to the prevailing soil and terrain constraints. A constraint classification has been formulated and has been applied to each grid-cell of the land resources inventory. The constraints considered include:

- Terrain-slope constraints
- Soil depth constraints
- Soil fertility constraints
- Soil drainage constraints
- Soil texture constraints
- Soil chemical constraints
- Presence of miscellaneous land units

The results by grid-cell have been aggregated into countries and regions. They are presented in terms of six broad LGP classes (0 days, 1–59 days, 60–119 days, 120–179 days, 180–269 days, and $\geq$ 270 days).[3] Details of the constraint classification are listed in Appendix III (CD-ROM). Results are presented in Section 5.1, "Climate, Soil, and Terrain Constraints to Rain-fed Crop Production." The geographical distribution of constraints is shown in Plates 20–28 (CD-ROM).

Notes

[1] Based on a 3-carbon organic acid (3-phosphoglyceric acid).

[2] Based on a 4-carbon organic acid (malate and aspartate).

[3] In tropical and subtropical lowland zones, where LGP$_{t=5}$ is 365 days, these broad LGP classes are referred to as, respectively: hyper-arid areas (LGP 0 days); arid areas (LGP 1–59 days); dry semi-arid areas (LGP 60–119 days); moist semi-arid areas (LGP 120–179 days); subhumid areas (180–269 days); and humid areas (LGP $\geq$ 270 days).

4

Crop/LUT Productivity

4.1 Introduction

This chapter presents the methodology and procedures for the assessment of land productivity potentials for rain-fed and irrigated conditions, respectively. For determining irrigated land productivity potentials, it has been assumed that (i) water resources of good quality are available, and (ii) irrigation infrastructure is in place. In other words, the procedures identify areas where climate, soils, and terrain permit irrigated crop cultivation, but do not assess availability of sufficient water supply. Note, however, that GAEZ could readily be linked to watershed data to define limits to water availability.

For the assessment of rain-fed land productivity, a water-balance model is used to quantify the beginning and duration of the period when sufficient water is available to sustain crop growth. Soil moisture conditions together with other climate characteristics (radiation and temperature) are used in a simplified and robust crop growth model to calculate potential biomass production and yield. To assess irrigated land productivity, the duration of the period with temperatures conducive to crop growth is used for matching the crop cycle length and for the calculation of biomass production and yield. The calculated potential yields are subsequently combined in a semi-quantitative manner with a number of reduction factors directly or indirectly related to climate (e.g., pests and diseases), and with soil and terrain conditions. The reduction factors, which are successively applied to the potential yields, vary with crop type, the environment (in terms of climate, soil, and terrain conditions), and assumptions about the level of inputs/management.

In order to ensure that the results of the suitability assessment relate to production achievable on a long-term basis, (i) fallow periods have been imposed, and (ii) terrain slopes have been excluded when inadequate for the assumed level of inputs/management or too susceptible to topsoil erosion.

4.2 Land Utilization Types

A critical step in implementing any AEZ application is the selection and description of land utilization types. The selection of crops for this GAEZ study is based on three considerations, namely: (i) to include the most important food crops;

(ii) to cover a wide range of natural environments, including those in temperate and boreal zones; and (iii) to include, for backward compatibility with earlier AEZ work, all crops previously covered.

In total, 154 rain-fed LUTs are distinguished (food, fiber, fodder crops, and pasture), each at three generic levels of inputs and management (high, intermediate, and low). For the irrigation land potential assessment, crop LUTs are used at two generic levels of inputs and management (high and intermediate). The full list of crop types is presented in *Table 4.1*.

Relevant crop adaptability and crop requirement data are stored in a crop catalog database. These data sets include for each crop/LUT (and by input level, where applicable) the following information:

(i) Crop characteristics, including crop growth cycle length; relative lengths of crop development stages; photosynthetic pathway; crop adaptability group (defining maximum rates of photosynthesis); development-stage-specific coefficients relating crop water requirements to reference evapotranspiration (K_c-factors, see FAO, 1992a); moisture-stress-related yield reduction coefficients (K_y-factors, see FAO, 1992a).
(ii) Parameters describing for both rain-fed and irrigated LUTs, the thermal requirements, growing period requirements, and soil and terrain requirements, respectively, that apply to tropical, subtropical, temperate, and boreal environments.
(iii) Factors converting biomass to useful products and commodity aggregates, such as harvest index; food content coefficients (energy, protein); extraction/conversion rates; crop by-product/residue coefficients; and commodity aggregation weights.

4.3 Climatic Suitability Analysis

The climatic suitability analysis entails matching crop/LUT requirements with prevailing climatic conditions. It involves the following activities:

(a) Compile crop adaptability inventory and define crop/LUT-specific temperature and moisture requirements;
(b) Match crop temperature requirements with prevailing temperature regime;
(c) Determine optimal cropping calendar and calculate potential biomass and yield;
(d) Calculate crop/LUT-specific water deficit and apply moisture-stress-related yield reduction factors (rain-fed); calculate irrigation water requirements (irrigated);

Table 4.1. Crop types included in the GAEZ study.

Crops	Crop types	Climate zones
Cereals	(83)	
Wheat (hibernating)	4	Boreal, temperate, and subtropics
Wheat (non-hibernating)	12	Boreal, temperate, subtropics, and tropics
Rice, japonica (wetland)	4	Tropics, subtropics, and temperate
Rice, indica (wetland)	4	Tropics and subtropics
Rice (dryland)	3	Tropics
Maize (grain)	13	Tropics, subtropics, and temperate
Maize (silage)	6	Subtropics and temperate
Barley (hibernating)	4	Boreal, temperate, and subtropics
Barley (non-hibernating)	12	Boreal, temperate, subtropics, and tropics
Sorghum	7	Tropics, subtropics, and temperate
Pearl millet	2	Tropics
Foxtail millet (*Setaria*)	4	Subtropics and temperate
Rye (hibernating)	4	Temperate and subtropics
Rye (non-hibernating)	4	Boreal, temperate, and subtropics
Roots and tubers	(8)	
White potato	4	Boreal, temperate, subtropics, and tropics
Cassava	1	Tropics
Sweet potato	3	Subtropics and tropics
Pulses	(17)	
Phaseolus bean	9	Tropics, subtropics, and temperate
Chickpea	5	Subtropics and tropics
Cowpea	3	Tropics
Oil crops	(25)	
Soybean	6	Tropics, subtropics, and temperate
Rape (hibernating)	2	Temperate and subtropics
Rape (non-hibernating)	6	Temperate, subtropics, and tropics
Groundnut	3	Tropics, subtropics, and temperate
Sunflower	6	Temperate, subtropics, and tropics
Oil palm	1	Tropics and subtropics
Olive	1	Subtropics and temperate
Fiber crops	(7)	
Cotton	7	Tropics, subtropics, and temperate
Sugar crops	(6)	
Sugarcane	1	Tropics and subtropics
Sugar beet	5	Temperate and subtropics
Fruit crops	(1)	
Banana/plantain	1	Tropics and subtropics
Forage/fodder	(7)	
Forage legume (alfalfa)	1	Temperate and subtropics
Pasture grasses	4	Boreal, temperate, subtropics, and tropics
Pasture legumes	2	Boreal, temperate, subtropics, and tropics
Total	154	

Table 4.2. Suitability classes.

Suitability class	Percentage of maximum yield attainable
Very suitable (VS)	80–100
Suitable (S)	60–80
Moderately suitable (MS)	40–60
Marginally suitable (mS)	20–40
Not suitable (NS)	0–20

(e) Formulate crop/LUT-specific agro-climatic constraints, accounting for expected yield losses due to factors related to climate conditions, such as incidence of pests, diseases, and weeds; workability; and frost occurrence. Apply relevant reduction factors to estimate average attainable yield in each grid-cell.

The results of the climatic suitability analysis are calculated in three steps. Step 1 produces a grid-cell-specific agro-climatic characterization, including calculation of thermal climates, temperature profiles, and temperature and moisture growing period characteristics. Step 2 calculates temperature and radiation limited potential crop yields, quantifies moisture-stress-related yield reductions, and determines optimal crop calendars. Finally, Step 3 applies reduction factors to account for yield-reducing of agro-climatic constraints and provides the attainable crop yields. Results have been classified in five basic suitability classes according to attainable yield ranges relative to maximum potential crop yields (*Table 4.2*). Maximum potential crop yields are calculated for tropical, subtropical, and temperate/boreal climate zones, respectively.

4.3.1 Crop thermal requirements and thermal suitability

Temperature and day-length influence the developmental sequence of crop growth in relation to crop phenology. Crop thermal and day-length requirements for both photosynthesis and phenological development have been taken into account in three regards:

(i) Crops have been classified for day-length requirements. For example, short-day crops have been restricted to the lower-latitude tropical zones while long-day crops have been restricted to the higher-latitude boreal and temperate zones.

(ii) A thermal requirements scheme has been devised for each of the 154 crop/LUTs, such that: (a) it covers sufficiently the requirements for photosynthesis and growth, and considers requirements for phenological development of each crop type, and (b) it is applicable in equatorial tropics, and in seasonal subtropical, temperate, and boreal climates. The thermal requirements have been formulated in accordance with the temperature profiles which reflect seasonality characteristics of the individual grid-cells (see Section 3.2.3). In this way, the temperature requirements are expressed in terms of the length of periods (duration in days) of the crop cycle falling into temperature intervals of 5°C, separately for increasing and decreasing temperatures. The latter accord with the "A" and "B" type temperature profile periods as described in Section 3.2.3.

The procedures for matching thermal requirements to crop temperature profiles yield three cases: *Optimal match* when photosynthesis and phenological temperature requirements are fully met; *Suboptimal match* when the requirements are just sufficiently met for growth and development; and *Not suitable* when temperature requirements for either photosynthesis or for phenological development are not met.

(iii) Crop growth cycle heat requirements (accumulated temperature in degree-days) have been compared with the accumulated temperature actually available in a grid-cell during the growth cycle. When heat requirements are not met, the temperature regime is considered not suitable and no further evaluation of the particular crop/LUT for such a grid-cell is undertaken.

In the grid-cells where thermal requirements of a particular crop/LUT are met in optimal or suboptimal terms, biomass and yield calculations are performed. *Figure 4.1* shows a representation of thermal requirements for winter wheat. Thermal requirements for all the crops considered are presented in Appendix IV (CD-ROM).

4.3.2 Biomass and yield

The constraint-free crop yields calculated in the AEZ biomass model[1] reflect yield potentials with regard to temperature and radiation regimes prevailing in the respective grid-cells. This basically eco-physiological model (Kassam, 1977) requires the following crop characteristics: (i) length of growth cycle (days from emergence to full maturity); (ii) length of yield formation period; (iii) leaf area index (LAI) at maximum growth rate; (iv) harvest index (H_i); (v) crop adaptability group; and (vi) sensitivity of crop growth cycle length to heat provision. The biomass calculation also includes simple procedures to account for different levels of atmospheric CO_2 concentrations (Fischer and van Velthuizen, 1996). Appendix VI (CD-ROM) provides details of the calculation procedures and Appendix VII (CD-ROM) lists the model parameters.

Crop		Winter wheat (C3/I)			
Climates		Subtropics, temperate, boreal			
Photosensitivity		Day-neutral/Long day			
Growth cycles (days)[a]		a + b 30 + 90, 35 +105, 40 +120, 45 +135			
Temperature periods[b]		Suboptimal conditions Percentage of growth cycle		Optimal conditions Percentage of growth cycle	
		1st req.	2nd req.	1st req.	2nd req.
A9	$<$ –5°C	0	0	0	0
A8	–5–0°C	0	0	0	0
A7	0–5°C	0	0	0	0
A6	5–10°C	≤50 % b	$>$ 16.7 % b	≤50 % b	$>$ 16.7 % b
A5	10–15°C				
A4	15–20°C	≤100 % b		≤100 % b	
A3	20–25°C				
A2	25–30°C		≤33.3 % b		≤33.3 % b
A1	$>$ 30°C	0	0	0	0
B1	$>$ 30°C	0	0	0	0
B2	30–25°C				
B3	25–20°C	≤50 % b		≤50 % b	
B4	20–15°C		100% a		100% a
B5	15–10°C				
B6	10–5°C				
B7	5–0°C	0	0	0	0
B8	0–5°C	0	0	0	0
B9	$<$ –5°C	0	0	0	0
Accumulated temperature during growth cycle[c] (TS_{gc})		$TS_{gc} > 1,300$ (post dormancy)		$TS_{gc} > 1,500$ (post dormancy)	
$LGP_{t=5}$		$<$ 365		$<$ 365	
Dormancy		Required		Required	
Permafrost tolerance		No permafrost		No permafrost	

[a] a: pre-dormancy part of growth cycle; b: post-dormancy part of growth cycle.
[b] A9–A1: temperature periods with increasing temperatures, i.e., during winter to summer; B1–B9: temperature periods with decreasing temperatures, i.e., from summer to winter.
[c] Accumulated temperature during post-dormancy part of growth cycle.

Figure 4.1. Temperature profile and thermal requirements for winter wheat.

The results of the biomass and yield calculation depend on the timing of the crop growth cycle (crop calendar). Maximum biomass and yields are separately calculated for irrigated and rain-fed conditions, as follows:

Irrigation: For each day within the window of time when crop temperature requirements are met optimally or at least suboptimally,[2] the period resulting in the highest biomass and yield is selected to represent the production and crop calendar of the respective crop/LUT for a particular grid-cell.

Rain-fed: Within the window with optimal or suboptimal temperature conditions, and starting within the duration of the moisture growing period, the period resulting in the highest expected (moisture-limited) yield is selected to represent maximum biomass and yield for rain-fed conditions of the respective crop/LUT for a particular grid-cell. Moisture limited yields are calculated by applying crop-stage-specific and total growing period yield reduction factors (FAO, 1979; FAO 1992a). The yield reduction factors relate relative yield decrease, expressed as $(1 - Y_a/Y_m)$, to relative evapotranspiration deficit $(1 - ET_a/ET_m)$. In this formulation, Y_a and Y_m denote water-limited and potential yield, respectively; ET_a and ET_m refer to crop-specific actual and potential evapotranspiration in a grid-cell. The obtained relative yield decrease is then applied to the calculated temperature/radiation-limited biomass and yield.

In other words, for each crop type and grid-cell, the starting and ending dates of the crop growth cycle are determined optimally to obtain the best possible crop yields, separately for rain-fed and irrigated conditions. This procedure also guarantees maximum adaptation in simulations with year-by-year historical weather conditions, or under climate distortions applied in accordance with various climate change scenarios. Hence, the AEZ method simulates a “smart” farmer. Results of the biomass and yield calculations can be presented in tabular or in map form. For instance, Plate 10 (CD-ROM) presents a map of temperature- and radiation-limited yields for wheat.

4.3.3 Crop moisture requirements and growing period suitability

For most crops, crop water requirements are well established and widely published. Various aspects relevant to crop moisture requirements are included in the crop catalog data files: crop growth cycle length, crop-stage-specific water requirement coefficients, moisture-deficit-related yield reduction coefficients.

To account for differences in soil types, the crop cycle matching and biomass calculations were performed for each of the six soil moisture storage capacity

($S_{\max}$) classes (see *Table 3.4* in Section 3.2.4). Moisture-limited yields of annual rain-fed crops have been calculated by applying crop-stage-specific and total-growing-period yield reduction factors in accordance with procedures developed by FAO (1992a) and as described in the calculation of biomass and yield. This allows the relevant result to be applied for each of the soil types occurring in a particular soil mapping unit of the FAO DSMW.

Perennial crops (i.e., cassava, sugar cane, banana, oil palm, olive, alfalfa, grass/legume mixtures, and grasses) are matched to moisture conditions of the calculated growing periods. This involves the following considerations: (i) how well does the crop growth cycle fit within the available total LGP? and (ii) how well are crop water requirements met by growing-period-quality parameters (e.g., ratio of actual over potential evapotranspiration (ET_a/ET_m), or type of growing periods)? Yield losses directly resulting from moisture constraints are quantified through adjustments of both the leaf area index and harvest index. For example, if the crop growth cycle is curtailed because the LGP is insufficient, the leaf area index is reduced proportionately relative to the LAI of the normal growth cycle considered. When the yield formation period is curtailed because the growing period is shorter, the harvest index (H_i) is reduced proportionately in relation to the standard H_i of the reference yield formation period.

Losses in marketable value of the produce due to poor yield quality as influenced by incomplete yield formation, however, cannot be accounted for in the biomass and yield calculations. These and other losses have been evaluated separately and are referred to as *agro-climatic* constraints.

4.3.4 Agro-climatic constraints

At the stage of computing potential biomass and yields, no account is taken of the climate-related effects operating through pests, diseases, and workability. To arrive at realistic estimates of attainable crop yields, such effects need to be included. Precise estimates of their impacts are very difficult to obtain for a global study. It has been achieved here by quantifying the constraints in terms of reduction ratings, according to different types of constraints and their severity for each crop, varying by length of growing period zone and by level of inputs. This last subdivision is necessary to take account of the fact that some constraints, such as bollworm on cotton, are present under low input conditions, but are controllable under high input conditions in certain growing period zones. While some constraints are common to all input levels, others (e.g., poor workability through excess moisture) are more applicable to high input conditions with mechanized cultivation.

Agro-climatic constraints cause direct or indirect losses in the yield and quality of produce. Yield losses in a rain-fed crop due to agro-climatic constraints have been formulated based on principles and procedures originally proposed in FAO (1978-81a). Details of the conditions that are influencing yield losses are listed below.

(i) How well the crop growth cycle fits within the LGP

When the growing period is shorter than the growth cycle of the crop, from sowing to full maturity, there is loss of yield. The biomass and yield calculations account for direct losses by appropriately adjusting LAI and harvest index (see Section 4.3.2). However, the loss in the marketable value of the produce due to poor quality of the yield as influenced by incomplete yield formation (e.g., incomplete grain filling in grain crops resulting in shriveled grains or yield of a lower grade, or incomplete bulking in root and tuber, leading to a poor grade of ware), is not accounted for in the biomass and yield calculations. This loss is to be considered as an agro-climatic constraint in addition to the quantitative yield loss due to curtailment of the yield formation period. Yield losses can also occur when the LGP is much longer than the length of the growth cycles. These losses operate through yield and quality reducing effects of (a) pests, diseases, and weeds; (b) climatic factors affecting yield components and yield formation; and (c) climatic conditions affecting the efficiency of farming operations.

(ii) The degree of water stress during the growing period

Water stress generally affects crop growth, yield formation, and quality of produce. The yield-reducing effects of water stress varies from crop to crop. The total yield impact can be considered in terms of (a) the effect on the growth of the whole crop, and (b) the effect on yield formation and quality of produce. For some crops, the latter effect can be more severe than the former, particularly where the yield is a reproductive part (e.g., cereals), and yield formation depends on the sensitivity of floral parts and fruit set to water stress (e.g., silk drying in maize).

(iii) Pests, diseases, and weeds

To assess the agro-climatic constraints of the pest, disease, and weed complex, the effects on yields that operate through loss in crop growth potential (e.g., pests and diseases affecting vegetative parts in grain crops) have been separated from effects on yield that operate directly on yield formation and quality of produce (e.g., cotton stainer affecting lint quality, grain mold in sorghum affecting both yield and grain quality).

(iv) Climatic factors directly or indirectly reducing yield and quality of produce

These include problems of poor seed set and/or maturity under cool or low temperature conditions, problems of seed germination in the panicle due to wet conditions at the end of grain filling, problems of poor quality lint due to wet conditions during the time the cotton boll opens, problems of poor seed set in wet conditions at the time of flowering in some grain crops, and problems of excessive vegetative growth and poor harvest index due to high night-time temperature or low diurnal range in temperature.

(v) Climatic factors affecting the efficiency of farming operations and costs of production

Farming operations include those related to land preparation, sowing, cultivation and crop protection during crop growth, and harvesting (including operations related to handling the produce during harvest and the effectiveness of being able to dry the produce). Agro-climatic constraints in this category are essentially workability constraints, which primarily account for excessive wetness conditions. Limited workability can cause direct losses in yield and quality of produce, and/or impart a degree of relative unsuitability to an area for a given crop from the point of view of how effectively crop cultivation and produce handling can be conducted at a given level of inputs.

(vi) Frost hazard and extreme temperature events

The risk of occurrence of late and early frost increases substantially when mean temperatures drop below 10°C. Hence, the length of the thermal growing period with temperatures above 10°C (LGP$_{t=10}$) in a grid-cell has been compared with the growth cycle length of frost-sensitive crops. When the crop growth cycle is slightly shorter than LGP$_{t=10}$, the constraints related to frost risk are adjudged moderate; when the growth cycle is very close or equal to LGP$_{t=10}$, the constraints have been adjudged to be severe.

The agro-climatic constraints described above are closely related to prevailing climate conditions. For convenience they have been arranged in five groups as follows:

(a) Yield losses due to water stress constraints on crop growth (e.g., rainfall variability);
(b) Yield losses due to the effect of pests, diseases, and weed constraints on crop growth;

(c) Yield losses due to stress from climatic conditions, excess wetness, and pests and diseases constraints on yield components and yield formation (e.g., affecting quality of produce);
(d) Yield losses due to workability constraints (e.g., wetness causing produce handling difficulties); and
(e) Yield losses due to occurrence of early or late frosts.

In general, as the duration of LGP and wetness increases, constraints from pests and diseases (groups “b” and “c”) become increasingly severe, particularly to low input cultivators. As the LGP gets very long, even the high input level cultivator cannot keep these constraints under control and they become severe yield-reducing factors at all three levels of inputs. Other factors, such as poor pod set in soybean or poor quality in short LGP zones, are of similar severity for all three levels of inputs. Difficulties in lifting root crops under dry soil conditions (short LGP group “d”) are rated more severely under the high level of inputs (mechanized) than under intermediate and low level of inputs. For irrigated production, the “c” constraint is applied only at the wet end, i.e., more than 300 days in the example for winter wheat shown in *Table 4.3*.

Although the constraints of group “d” are not actually direct yield losses, such constraints do mean, for example, that the high input level mechanized cultivator cannot get onto the land to carry out operations. In practice, this results in yield reductions. For the low input cultivator, excessive wetness could mean, for example, that the produce is too wet to handle and remove, and again losses would be incurred even though the produce may be standing in the field. Also included in this group are constraints due to the cultivator having to use longer duration cultivars that permit harvesting under dry conditions. The use of such cultivars incurs yield restrictions, and such circumstances under wet conditions have therefore been incorporated in the severity ratings of agro-climatic constraints in group “d”.

The availability of historical rainfall data has made it possible to derive the effect of rainfall variability through year-by-year calculation of yield losses due to water stress. Therefore the “a” constraint, related to rainfall variability, is no longer applied. However the “a” constraint has been retained in the agro-climatic constraints database for use with data sets containing average rainfall data and for comparison with results of the currently used year-by-year analysis.

The “b” and “d” constraints and part of the “c” are related to wetness. The ratings of these constraints have been linked to the LGP. It appears however, that in different climate zones, wetness conditions, traditionally expressed as P/ET_0 ratios, vary considerably for similar LGPs. Long LGPs with relatively low P/ET_0 ratios occur generally in subtropical, temperate, and boreal zones, while relatively high ratios occur in the tropics.

Table 4.3. Agro-climatic constraints yield reduction factors (%) for winter wheat (growth cycle: 40 days pre-dormancy + 120 days post-dormancy).

LGP	60–89	90–119	120–149	150–179	180–209	210–239	240–269	270–299	300–329	330–364	365–	365+
Low inputs												
a[a]	50	50	25	25	0	0	0	0	0	0	0	0
b	0	0	0	0	0	0	25	25	25	25	25	25
c	25	25	25	0	0	0	0	0	25	25	50	50
d	0	0	0	0	0	0	0	0	0	25	50	50
Intermediate inputs												
a	50	50	25	25	0	0	0	0	0	0	0	0
b	0	0	0	0	0	0	0	25	25	25	25	25
c	25	25	25	0	0	0	0	0	25	25	50	50
d	0	0	0	0	0	0	0	0	0	25	50	50
High inputs												
a	50	50	25	25	0	0	0	0	0	0	0	0
b	0	0	0	0	0	0	0	0	25	25	25	25
c	25	25	0	0	0	0	0	0	0	25	25	50
d	0	0	0	0	0	0	0	25	25	25	50	50
$LGP_{t=10}$	60–89	90–119	120–149	150–179	180–209	210–239	240–269	270–299	300–329	330–364	365	
All input levels												
e	100	50	25	0	0	0	0	0	0	0	0	

[a] The “a” constraint (yield losses due to rainfall variability) is not applied in the current assessment. This constraint has become redundant due to explicit quantification of yield variability through the application of historical rainfall data sets.

To account for these significant differences in wetness conditions of long LGPs ($>$ 225 days), agro-climatic constraints have been related to P/ET_0 ratios by calculating *equivalent* LGPs, i.e., adjustments where P/ET_0 ratios were below average. The equivalent LGPs are then used in the application of the "b," "c," and "d" constraints.

Table 4.3 presents an example of agro-climatic constraints for winter wheat. For irrigated production, only the agro-climatic constraints related to excess wetness apply. A listing of the agro-climatic constraint parameters considered for all the crop/LUTs are presented in Appendix VIII (CD-ROM).

The application of the agro-climatic constraints to the combined results of temperature suitability and the biomass and yield calculations (see previous Sections) provides agro-climatic suitabilities. Plates 11 and 12 (CD-ROM) present examples of agro-climatic suitability maps for rain-fed and rain-fed plus irrigated wheat production at the high level of inputs.

4.4 Growing Period Suitability for Water-collecting Sites

In water-collecting sites, substantially more water can be available to plants as compared to upland situations. Water-collecting sites are difficult to locate in a global study, but can be approximately determined on the basis of the prevalence of specific soil types. Fluvisols[3] and, to a lesser extent, Gleysols[4] typically represent the flat terrain of alluvial valleys and other water-collecting sites.

The cultivation of Fluvisols (under unprotected natural conditions) is determined by frequency, duration, and depth of flooding. The flooding attributes are generally controlled by external factors, such as a river's flood regime, which – in turn – is influenced by hydrological features of the catchment area and catchment/site relations, rather than by the amount of "on site" precipitation.

Therefore, with the exception of wetland crops, the cultivation of these soils is mainly confined to post-flood periods, with crops growing on residual soil moisture. The flooding regime in arid and semi-arid zones is erratic. Some years, severe flash floods may occur; in other years, no floods occur at all. In subhumid and humid zones, flooding is more regular but duration and depth of flooding may vary widely from year to year.

Gleysols are not directly affected by river flooding. These soils are, however, frequently situated in low-lying water-collecting sites and when not artificially drained, the Gleysols may be subject to water-logging or even inundation as a result of combined high groundwater tables and ponding rainwater. In arid and semi-arid areas, these soils are cultivated in the later part of and after rainy seasons; the crops grow and mature on residual soil moisture. In subhumid and humid

Table 4.4. The application of Fluvisol suitability ratings and soil unit suitability ratings of artificially drained Gleysols.

	Fluvisols		Gleysols	
	Natural	Protected	Natural	Artificially drained
Rain-fed				
High level inputs	No	Yes	No	Yes
Intermediate level inputs	50%	50%	50%	50%
Low level inputs	Yes	No	Yes	No
Irrigation				
High level inputs	No	Yes	No	Yes
Intermediate level inputs	50%	50%	50%	50%

areas, Gleysols without artificial drainage often remain waterlogged for extensive periods, rendering them unsuitable for cultivation of dryland crops.

On both Fluvisols and Gleysols, crops of short duration that are adapted to growing and producing yields on residual soil moisture and which are tolerant to flooding, water-logging, and high groundwater tables, can be found producing satisfactorily outside the growing period defined by the local rainfall regime. Therefore, a separate crop suitability classification for water-collecting sites is required. In compiling this classification, the logic of the original AEZ study (FAO, 1978-81a) has been followed. This includes accounting for crop-specific tolerances to excess moisture (high groundwater, water-logging, and flooding/inundation) and the use of available estimates of flooding regimes of the Fluvisols. Since Gleysols are mostly, but not necessarily, subjected to water-logging and inundation just like the "natural Fluvisols," it was decided to treat Gleysols with terrain-slopes of less than 2% the same as Fluvisols.

In many parts of the world, the flooding of Fluvisols is increasingly being controlled with dikes and other protection means. Fluvisols, under protected conditions, do not benefit from additional water supply and regular fresh sediment deposits, nor do they suffer from flooding. The moisture regime of Fluvisols under these protected conditions is similar to that of other soils, and therefore protected Fluvisols are treated according to the procedures used for crops in upland conditions.

In a similar way, Gleysols may be artificially drained, thereby diminishing a major limitation for the cultivation of these soils. For areas where the Gleysols have been drained, a revised (i.e., less severe) set of soil ratings is used and the rules for natural Fluvisols are not applied.

Since spatial details of the occurrence of protected Fluvisols and artificial drainage of Gleysols are not available at the global scale, these factors are assumed to be linked to the level of inputs/management. The application of Fluvisol suitability ratings and soil unit suitability ratings of artificially drained Gleysols are presented in *Table 4.4*.

The moisture suitability ratings devised for unprotected Fluvisols and Gleysols without artificial drainage are organized in ten groups of crops with comparable growth cycle lengths and similar tolerances to high groundwater levels, waterlogging, and flooding. The rating tables are presented in Appendix IX (CD-ROM).

4.5 Agro-edaphic Suitability Analysis

Adequate agricultural exploitation of the climatic potentials and maintenance of land productivity largely depend on soil fertility and the management of soils on an ecologically sustained basis. Soil fertility is concerned with the ability of the soil to retain and supply nutrients and water, so that crops can utilize fully the climatic resources of a given location. The fertility of a soil is determined by both its physical and chemical properties. An understanding of these factors and insight into their interrelations is essential to the effective exploitation of climate, terrain, and crop resources for optimum use and production.

From the basic soil requirements of crops, several soil characteristics have been established that are related to crop yield response. For most crops and cultivars, optimal, suboptimal, marginal, and unsuitable levels of these soil characteristics are known and have been quantified. Beyond critical ranges, crops cannot be expected to yield satisfactorily unless special precautionary management measures are taken. Soil suitability classifications are based on knowledge of crop requirements, of prevailing soil conditions, and of applied soil management. In other words, soil suitability classifications quantify in broad terms the extent to which soil conditions match crop requirements under defined input and management circumstances. For a global study, this determination necessitates expert judgment and a semi-quantitative approach.

4.5.1 Soil suitability evaluation for rain-fed crop production

FAO's agro-edaphic suitability classification used in AEZ is to a large extent based on experience documented by Prof. C. Sys and others (FAO, 1978-81a; Sys and Riquier, 1980; FAO, 1984b; FAO, 1985; Nachtergaele, 1988; Sys, 1990; Sys *et al*., 1993). The agro-edaphic suitability classification has been intensively used by FAO and other organizations, at various scales in many countries and regions; it passed through several international expert consultations, and hence it constitutes the most recent consolidation of expert knowledge. In this system, a suitability rating is proposed for each soil unit, by individual crops at three defined levels of inputs and management circumstances. The agro-edaphic suitability rating is based on a comparison of soil requirements of crops and prevailing edaphic conditions. Data available from various sources have been summarized by Sys *et al*. (1993).

The source of soil information is primarily the digital version of the FAO/UNESCO *Soil Map of the World* (FAO, 1995c). A tabulation of the soil ratings by FAO '74 soil unit for all crop/LUTs considered is presented in Appendix X (CD-ROM). Soil phase suitability ratings are listed in Appendix XI (CD-ROM). Modifications of soil suitability ratings for soil units with coarse textures are treated according to procedures presented in FAO (1978-81a).

4.5.2 Terrain suitability evaluation for rain-fed crop production

Topography influences agricultural land use in many ways. Farming practices are, by necessity, adapted to terrain slope, slope aspect, slope configuration, and micro-relief. For instance, steep irregular slopes are not practical for mechanized cultivation, while these slopes might very well be cultivated with adapted machinery and hand tools.

Sustainable agricultural production on sloping land is primarily concerned with the prevention of erosion of topsoil and the decline of fertility. Usually this is achieved by combining special crop management and soil conservation measures. Slopes cultivated with crop/LUTs providing insufficient soil protection and without applying adequate soil conservation measures cause a considerable risk of accelerated soil erosion. In the short term, cultivation of slopes might lead to yield reductions arising from loss of applied fertilizer and fertile topsoil. In the long term, such cultivation will result in losses of land productivity: truncation of the soil profile will occur, and this consequently will reduce natural soil fertility and available soil moisture.

Rain-fed annual crops are the most critical in causing topsoil erosion, because of their particular cover dynamics and management. The terrain-slope suitability rating used in the GAEZ study captures the factors, described above, that influence production sustainability. This is achieved through: (i) defining permissible slope ranges for cultivation of various crop/LUTs and setting maximum slope limits; (ii) for slopes within the permissible limits, accounting for likely yield reduction due to loss of fertilizer and topsoil; and (iii) distinguishing among farming practices ranging from manual cultivation to fully mechanized cultivation.

Ceteris paribus – i.e., under similar crop cover, soil erodibility, and crop and soil management conditions – soil erosion hazards largely depend on amount and intensity of rainfall. Data on rainfall amount is available on a monthly basis in the 0.5 degree latitude/longitude climate databases. Rainfall intensity or energy, which is relevant for soil erosion, is not estimated in these data sets.

To account for clearly existing differences in both amount and within-year distribution of rainfall, use has been made of the modified Fournier index (F_m), which reflects the combined effect of rainfall amount and distribution (FAO/UNEP, 1977), as follows:

$$F_m = 12 \sum_{i=1}^{12} \frac{p_i^2}{P_{\text{ann}}} , \tag{4.7}$$

where p_i is precipitation of month i, and P_{ann} is total annual precipitation.

When precipitation is equally distributed during the year, i.e., in each month one-twelfth of the annual amount is received, then the value of F_m is equal to P_{ann}. On the other extreme, when all precipitation is received within one month, the value of F_m amounts to twelve times P_{ann}. Hence, F_m is sensitive to both total amount and distribution of rainfall and is limited to the range of $P_{\text{ann}} \leq F_m \leq 12P_{\text{ann}}$. The F_m index has been calculated for all 0.5 degree grid-cells of the climatic inventory. The results have been grouped in six classes, namely: $F_m <$ 1300, 1300–1800, 1800–2200, 2200–2500, 2500–2700, and $F_m > 2700$. These classes were determined on the basis of regression analysis, correlating different ranges of LGP zones with levels of the Fournier index F_m. This was done to incorporate the improved climatic information on within-year rainfall distribution into GAEZ while keeping consistency with earlier procedures of the methodology, which were defined by LGP classes.

Slope ratings are defined for the seven slope range classes used in the land resources database, namely: 0–2% flat, 2–5% gently sloping, 5–8% undulating, 8–16% rolling, 16–30% hilly, 30–45% steep, and $>$ 45% very steep. The following suitability rating classes are employed:

S1	Optimal conditions
S2	Suboptimal conditions
S1/S2	50% optimal and 50% suboptimal conditions
S2/N	50% suboptimal and 50% not suitable conditions
N	Not suitable conditions

Table 4.5 presents terrain-slope ratings under rain-fed conditions for eight crop groups at three levels of inputs and management in grid-cells with rainfall such that the level of the Fournier index $F_m <$ 1300. Additional ratings, for levels of the index $F_m >$ 1300, are listed in Appendix XIV (CD-ROM).

4.5.3 Soil and terrain suitability evaluation for irrigated crop production

The evaluation procedures for gravity irrigation suitability cover the dryland crops and wetland rice, at both intermediate and high levels of management and input

Table 4.5. Terrain-slope ratings for rain-fed conditions ($F_m < 1300$).

Slope gradient classes	0–2%	2–5%	5–8%	8–16%	16–30%	30–45%	>45%
High inputs							
Annuals 1	S1	S1	S1	S1/S2	N	N	N
Annuals 2	S1	S1	S1	S1/S2	N	N	N
Wetland rice	S1	S1/S2	S2/N	N	N	N	N
Sugarcane	S1	S1	S1/S2	S2/N	N	N	N
Olive	S1	S1	S1	S2	S2/N	N	N
Perennials	S1	S1	S1	S2	N	N	N
Pasture	S1	S1	S1	S1	S2/N	N	N
Forage legumes	S1	S1	S1	S1/S2	N	N	N
Intermediate inputs							
Annuals 1	S1	S1	S1	S1/S2	S2	N	N
Annuals 2	S1	S1	S1	S1/S2	S2	N	N
Wetland rice	S1	S1/S2	S2	N	N	N	N
Sugarcane	S1	S1	S1/S2	S2/N	N	N	N
Olive	S1	S1	S1	S1/S2	S2	N	N
Perennials	S1	S1	S1	S2	S2/N	N	N
Pasture	S1	S1	S1	S1	S1/S2	S2/N	N
Forage legumes	S1	S1	S1	S1	S1/S2	S2/N	N
Low inputs							
Annuals 1	S1	S1	S1	S1	S2	N	N
Annuals 2	S1	S1	S1	S1/S2	S2	N	N
Wetland rice	S1	S1/S2	S2	N	N	N	N
Sugarcane	S1	S1	S1/S2	S2/N	N	N	N
Olive	S1	S1	S1	S1/S2	S2	S2/N	N
Perennials	S1	S1	S1	S2	S2/N	N	N
Pasture	S1	S1	S1	S1	S1/S2	S2/N	N
Forage legumes	S1	S1	S1	S1	S1/S2	S2/N	N

Crop groups:
Annuals 1: wheat, barley, rye.
Annuals 2: maize, sorghum, pearl millet, foxtail millet, white potato, sweet potato, phaseolus bean, chickpea, cowpea, soybean and groundnut, sunflower, cotton, sugar beet, rape.
Perennials: cassava, oil palm, banana, plantain.

circumstances. Three important assumptions have been made in setting up the procedures: firstly, water resources of good quality are available; secondly, irrigation infrastructure is in place; and thirdly, the crop-specific soil limitations for rain-fed production (such as limitations imposed by soil rooting conditions, soil nutrient availability and soil nutrient retention capacity, soil toxicity, soil salinity, soil alkalinity, and calcium carbonate and gypsum content) also apply to irrigation. For irrigation, these limitations are assumed to be similar or more severe. (In arid and hyperarid areas only Fluvisols, Gleysols and soils with phreatic phase have been considered for the assessment of irrigation suitability.) Note, however, that the GAEZ assessment does not provide a quantification of irrigation water availability.

Table 4.6. Terrain-slope ratings for gravity irrigation.

Slope gradient classes	0–2%	2–5%	5–8%	8–16%	16–30%	30–45%	$> 45\%$
High inputs							
Annuals 1	S1	S1	S2/N	N	N	N	N
Annuals 2	S1	S1/S2	S2/N	N	N	N	N
Wetland rice	S1	S1/S2	N	N	N	N	N
Sugarcane	S1	S1/S2	S2/N	N	N	N	N
Olive	S1	S1/S2	S2/N	N	N	N	N
Perennials	S1	S1/S2	S2/N	N	N	N	N
Pasture	S1	S1	S2/N	N	N	N	N
Forage legumes	S1	S1	S2/N	N	N	N	N
Intermediate inputs							
Annuals 1	S1	S1	S1/S2	S2/N	N	N	N
Annuals 2	S1	S1/S2	S2/N	N	N	N	N
Wetland rice	S1	S1/S2	N	N	N	N	N
Sugarcane	S1	S1/S2	S2/N	N	N	N	N
Olive	S1	S1/S2	S2/N	N	N	N	N
Perennials	S1	S1/S2	S2/N	N	N	N	N
Pasture	S1	S1	S1/S2	S2/N	N	N	N
Forage legumes	S1	S1	S1/S2	S2/N	N	N	N

Crop groups:
Annuals 1: wheat, barley, rye.
Annuals 2: maize, sorghum, pearl millet, foxtail millet, white potato, sweet potato, phaseolus bean, chickpea, cowpea, soybean and groundnut, sunflower, cotton, sugar beet, rape.
Perennials: cassava, oil palm, banana, plantain.

Nevertheless, it can generate useful information for integrated analysis at the watershed level.

The following land and soil characteristics have been interpreted specifically for the irrigation suitability classification: topography; soil texture; soil drainage; surface and subsurface stoniness; calcium carbonate levels; gypsum status; and salinity and alkalinity conditions. The main literature sources used in the interpretation include Sys *et al*. (1993), Sys and Riquier (1980), FAO (1985), FAO (1996), FAO (1976b), FAO/UNESCO (1974), and FAO/UNESCO/ISRIC (1990).

Topography

The dominant topographic factor governing the suitability of an area for gravity or sprinkler irrigation is the terrain slope. Other topographic factors, such as microrelief, have partly been accounted for in the soil unit and soil phase suitability classifications. Permissible slopes for irrigation depend on the type of irrigation systems and the assumed level of inputs and management.

Provided it is managed properly, gravity irrigation (basin, border, and furrow systems) is suitable for a large range of crops. It is used for terrain slopes up

Table 4.7. Terrain-slope ratings for sprinkler irrigation.

Slope gradient classes	0–2%	2–5%	5–8%	8–16%	16–30%	30–45%	> 45%
High inputs							
Annuals 1	S1	S1	S1/S2	S2/N	N	N	N
Annuals 2	S1	S1	S1/S2	S2/N	N	N	N
Wetland rice	N	N	N	N	N	N	N
Sugarcane	S1	S1	S1/S2	S2/N	N	N	N
Olive	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Perennials	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Pasture	S1	S1	S1	S1/S2	S2/N	N	N
Forage legumes	S1	S1	S1/S2	S2/N	N	N	N
Intermediate inputs							
Annuals 1	S1	S1	S1/S2	S2/N	N	N	N
Annuals 2	S1	S1	S1/S2	S2/N	N	N	N
Wetland rice	N	N	N	N	N	N	N
Sugarcane	S1	S1	S1/S2	S2/N	N	N	N
Olive	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Perennials	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Pasture	S1	S1	S1	S1/S2	S2/N	N	N
Forage legumes	S1	S1	S1/S2	S2/N	N	N	N

Crop groups:
Annuals 1: wheat, barley, rye.
Annuals 2: maize, sorghum, pearl millet, foxtail millet, white potato, sweet potato, phaseolus bean, chickpea, cowpea, soybean and groundnut, sunflower, cotton, sugar beet, rape.
Perennials: cassava, oil palm, banana, plantain.

to 5%. For "non-row crops" such as wheat, barley, pasture, and forage legumes, slopes up to 10% can be used with special systems such as corrugations. At these steeper slopes, irrigation efficiency is diminished. Poor uniformity of the water distribution leads to irregular stands of crops. Therefore, slopes between 5% and 10% are classified as suboptimal for all types of gravity irrigation.

Sprinkler irrigation systems include many types. They are generally more efficient than gravity systems but also much more expensive, and they require special management skills. Sprinklers can be used on somewhat steeper slopes than the gravity systems. However, some of the larger central pivot systems can only be used on flat or almost flat terrain. Small-scale systems are more suitable on sloping land. For perennials or well-established pastures, well-adapted systems may be used on slopes up to 24%. For annual crops, serious erosion risk starts at about 10–12% slopes, depending on soil erodibility, ground cover, and management. Sprinkler irrigation is obviously not suitable for wetland crops.

Tables 4.6 and *4.7* present terrain-slope suitability ratings, for gravity and sprinkler irrigation systems, respectively, for eight groups of crops at high and intermediate levels of inputs. The suitability rating classes are the same as for rain-fed conditions.

Table 4.8. Soil texture/clay mineralogy limitations for irrigation.

Major soil unit			Suitability	
			Dryland	Wetland
FAO '74	FAO '90	Soil unit	crops	rice
Acrisols (A)	Acrisols (AC)	All units	S1/S2	S2
Ferralsols (F)	Ferralsols (FR)	All units	S1/S2	S2
Nitosols (N)	Nitisols (NT)	All units	S1/S2	S2
Podzols (P)	Podzols (PZ)	All units	N	N
Arenosols (Q)	Arenosols (AR)	All units	N	N
Andosols (T)	Andosols (AN)	Tv, ANz	N	N
n.a.	Alisols (AL)	All units	S1/S2	S2
n.a.	Plinthosols (PT)	All units	S1/S2	S2

Soil texture

Soil texture provides a measure for permeability, and to some extent, for water retention capacity. Soils with potentially high percolation losses and soils with low water retention capacity, e.g., vitric Andosols, Arenosols, Podzols, and all soils with coarse textures have been considered not suited for gravity irrigation. For medium and fine textured soils excessive percolation and low water retention capacities are less relevant. However for Acrisols, Nitosols, and Ferralsols, the irrigation suitability ratings are slightly different as compared to rain-fed conditions, because of their specific clay mineralogy, which results in a relatively low water retention capacity and slightly higher percolation losses. The modifications related to texture/clay mineralogy are summarized in *Table 4.8*.

Soil drainage

Irrigation of dryland crops requires well drained soils to assure aeration and to avoid the danger of secondary salinization. Drainage conditions depend on depth and quality of groundwater. At present, this cannot be assessed on regional and global scales due to lack of systematic data. Soil drainage quantification, however, is available for the soil units of the FAO Legend '74 (FAO, 1995c). For wetland rice and dryland crops drainage requirements under irrigation are quite different from those under rain-fed conditions. Therefore, the following modifications to rain-fed suitability ratings were adopted (see *Table 4.9*).

Soil depth and soil stoniness

Under irrigated conditions, soil depth affects drainage, aeration, and water retention properties. Deep soils favor drainage and are therefore optimal for irrigation of dryland crops. Soils with impermeable layers favor maintenance of flooding conditions for wetland rice. Shallow soils such as Rendzinas (rendzic Leptosols)

Table 4.9. Soil drainage limitations for irrigation.

LUT	Soil drainage class	Suitability
Wetland rice	P	S1
	VP, I, MW, W	S2
	SE, E	N
Dryland crops	W	S1
	MW	S1/S2
	I, P	S2
	VP, SE, E	N

Drainage classes: VP = very poor; P = poor; I = imperfectly; MW = moderately well; W = well; SE = somewhat excessively; E = excessively.

and Rankers (umbric Leptosols) and soils with phases implying a reduction in soil depth have been reviewed and adjusted for irrigated conditions.

Surface stoniness affects soil workability. In addition, subsurface stoniness reduces water-holding capacity and increases infiltration rates. It is assumed that a level of more than 40 volume percent of coarse materials will markedly influence the water-balance in the soil profile (Sys and Riquier, 1980). To reflect these constraints, which specifically affect irrigation suitability, the soil phase suitability ratings for petric (skeletic) and stony (rudic) phases in FAO Legends have been adjusted from the rain-fed ratings. The soil phase ratings for irrigated crop production are presented in Appendix XI (CD-ROM).

Calcium carbonate

Calcium carbonate in the form of free lime in the soil profile affects soil structure and interferes with infiltration and evapotranspiration processes. It influences both the soil moisture regime and availability of nutrients. This, however, applies equally to rain-fed and irrigated cropping. Therefore, no changes are required to the crop-specific limitations as established for rain-fed cropping.

Gypsum

Gypsum interferes with water absorption and availability. Because gypsum is soluble in water, so-called dissolution depressions can be formed as a result of the application of irrigation water to gypsiferous soils. This renders soils with high gypsum content unsuitable for irrigation. These gypsiferous soils and soil phases are listed in *Table 4.10*.

Salinity and alkalinity

Irrigation in semi-arid and arid regions requires careful soil drainage (natural and/or artificial) to avoid irrigation-induced secondary salinization. It is assumed that,

Table 4.10. Soil units with gypsum limitations for irrigation.

Gypsiferous soil units		Gypsiferous soil phases	
FAO '74	FAO '90	FAO '74	FAO '90
Gypsic Yermosols	Gypsisols	Petrogypsic	Yermic
Luvic Yermosols	Calcic Gypsisols		
Gypsic Xerosols	Luvic Gypsisols		
	Haplic Gypsisols		
	Gypsic Kastanozems		
	Gypsic Regosols		
	Gypsic Solonchaks		
	Gypsic Solonetz		

where so required, appropriate drainage systems are in place and that irrigation water is non-saline. In this case no changes are necessary to the crop-specific suitability ratings as used for rain-fed cropping.

Alkalinity, expressed as sodium saturation, influences the structure stability of soils, which in turn affects infiltration rates and aeration of soils. The alkalinity (sodicity) constraints are equally important for rain-fed and irrigated conditions. Therefore, the crop-specific soil unit and soil phase ratings evaluated for rain-fed conditions remain unchanged for irrigated cropping.

4.6 Fallow Period Requirements

In their natural state, many soils, in particular in the tropics, cannot be continuously cultivated without undergoing degradation. Such degradation is marked by a decrease in crop yields and a deterioration of soil structure; nutrient status; and other physical, chemical, and biological attributes. Under traditional low input farming systems, this deterioration is kept in check by alternating some years of cultivation with periods of fallow. The length of the necessary rest period is dependent on inputs applied, soil and climate conditions, and crops. The main reason for incorporating fallow into crop rotations is to enhance sustainability of production through maintenance of soil fertility.

Regeneration of nutrients and maintenance of soil fertility under low input cultivation is achieved through natural bush or grass fallow. At somewhat higher inputs to soils, soil fertility is maintained through fallow that may include for a portion of time a grass, grass-legume ley, or a green-manure crop. Factors affecting changes in soil organic matter are reviewed in Nye and Greenland (1960) and Kowal and Kassam (1978). They include temperature, rainfall, soil moisture and drainage, soil parent material, and cultivation practices. The fallow factors used in the present GAEZ land potential are based on earlier work done in the context of

FAO's regional assessments (Young and Wright, 1980) and the Kenya AEZ study (FAO/IIASA, 1991).

The fallow factors have been established by main crop groups and environmental conditions. The crop groups include cereals, legumes, roots and tubers, and a miscellaneous group consisting of long term annuals/perennials. Fallow requirements have been assumed to be negligible for olive and oil palm. The environmental frame consists of individual soil units, thermal regimes, and moisture regimes. The thermal regimes are expressed in terms of annual mean temperatures of $>$ 25°C, 20–25°C, 15–20°C, and $< 15°$C. The moisture regimes are made up of five broad LGP ranges:$<$ 90 days, 90–120 days, 120–180 days, 180–270 days, and $>$ 270 days.

Appendix XII (CD-ROM) presents fallow-land requirements by thermal and moisture regimes imposed to maintain soil fertility. This factor is expressed as the percentage of time during the fallow/cropping cycle the land must be under fallow. For Fluvisols and Gleysols, fallow factors are lower because of their special moisture and fertility conditions.

At high levels of inputs and management, fallow requirements are uniformly set at 10%. At intermediate level of inputs, the fallow requirements are set at one third of the levels required under low level of inputs. In the present study, the fallow requirement factors have been applied for the estimations of annually available arable land.

4.7 Multiple Cropping Zones for Rain-fed Crop Production

In the GAEZ crop suitability analysis, the LUTs considered refer to single cropping of sole crops, i.e., each crop is presumed to occupy the land only once a year and in pure stand. Consequently, in areas where the growing periods are long enough to allow more than one crop to be grown in the same year or season, single crop yields do not reflect the full potential of total time and space available per unit area of land for rain-fed production.

To assess the multiple cropping potential, several multiple cropping zones have been defined by matching both growth cycle and temperature requirements of individual suitable crops with the time available for crop growth. For rain-fed conditions, this period is approximated by the LGP, i.e., the number of days during which both temperature and moisture conditions permit crop growth.

For the definition of multiple cropping zones, four types of crops are distinguished: thermophilic crops requiring warm temperatures, cryophilic crops performing best under cool and moderately cool conditions, hibernating crops, and

Table 4.11. Delineation of multiple cropping zones under rain-fed conditions in the tropics.

Zone	LGP	$LGP_{t=5}$	$LGP_{t=10}$	$TS_{t=0}$	$TS_{t=10}$	TS-$G_{t=5}$	TS-$G_{t=10}$
A[a]	–	–	–	–	–	–	–
B[b]	$\geq$ 45	$\geq$ 120	$\geq$ 90	$\geq$1,600	$\geq$ 1,200	–	–
C[c]	$\geq$ 220	$\geq$ 220	$\geq$ 120	$\geq$ 5,500	–	$\geq$ 3,200	$\geq$ 2,700
	$\geq$ 200	$\geq$ 210	$\geq$ 120	$\geq$ 6,400	–	$\geq$ 3,200	$\geq$ 2,700
	$\geq$ 180	$\geq$ 200	$\geq$ 120	$\geq$ 7,200	–	$\geq$ 3,200	$\geq$ 2,700
D[c]	$\geq$ 270	$\geq$ 270	$\geq$ 165	$\geq$ 5,500	–	$\geq$ 4,000	$\geq$ 3,200
	$\geq$ 240	$\geq$ 240	$\geq$ 165	$\geq$ 6,400	–	$\geq$ 4,000	$\geq$ 3,200
	$\geq$ 210	$\geq$ 240	$\geq$ 165	$\geq$ 7,200	–	$\geq$ 4,000	$\geq$ 3,200
E	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
F	$\geq$ 300	$\geq$ 300	$\geq$ 240	$\geq$ 7,200	$\geq$ 7,000	$\geq$ 5,100	$\geq$ 4,800
G	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
H	$\geq$ 360	$\geq$ 360	$\geq$ 330	$\geq$ 7,200	$\geq$ 7,000	–	–

[a] Applies if conditions for zone B ("single cropping") are not met.
[b] The program tests if at least one of the crop/LUTs is agro-climatically suitable in the respective grid-cell.
[c] Refers to, respectively, high-land, mid high-land, and lowland areas in the tropics.

wetland crops with specific water requirements. Furthermore, the crops are subdivided according to growth cycle length, namely of less or more than 120 days duration, respectively. According to the above criteria, the following nine zones were classified and mapped (see Plate 13, CD-ROM):

A. *Zone of no cropping* (too cold or too dry for rain-fed crops)
B. *Zone of single cropping*
C. *Zone of limited double cropping* (relay cropping; single wetland rice may be possible)
D. *Zone of double cropping* (sequential cropping; wetland rice not possible)
E. *Zone of double cropping* (sequential cropping; one wetland rice crop possible)
F. *Zone of limited triple cropping* (partly relay cropping; no third crop possible in case of two wetland rice crops)
G. *Zone of triple cropping* (sequential cropping of three short-cycle crops; two wetland rice crops possible)
H. *Zone of triple rice cropping* (sequential cropping of three wetland rice crops possible)

Delineation of multiple cropping zones for rain-fed conditions is solely based on agro-climatic attributes calculated during AEZ analysis. The following attributes were used in the definition of cropping zones:

Table 4.12. Delineation of multiple cropping zones under rain-fed conditions in subtropics and temperate zones.

Zone	LGP	$\text{LGP}_{t=5}$	$\text{LGP}_{t=10}$	$\text{TS}_{t=0}$	$\text{TS}_{t=10}$	$\text{TS-G}_{t=5}$	$\text{TS-G}_{t=10}$
A[a]	–	–	–	–	–	–	–
B[b]	$\geq$ 45	$\geq$ 120	$\geq$ 90	$\geq$ 1,600	$\geq$ 1,200	–	–
C	$\geq$ 180	$\geq$ 200	$\geq$ 120	$\geq$ 3,600	$\geq$ 3,000	$\geq$ 3,200	$\geq$ 2,700
D	$\geq$ 210	$\geq$ 240	$\geq$ 165	$\geq$ 4,500	$\geq$ 3,600	$\geq$ 4,000	$\geq$ 3,200
E	$\geq$ 240	$\geq$ 270	$\geq$ 180	$\geq$ 4,800	$\geq$ 4,500	$\geq$ 4,300	$\geq$ 4,000
F	$\geq$ 300	$\geq$ 300	$\geq$ 240	$\geq$ 5,400	$\geq$ 5,100	$\geq$ 5,100	$\geq$ 4,800
G	$\geq$ 330	$\geq$ 330	$\geq$ 270	$\geq$ 5,700	$\geq$ 5,500	–	–
H	$\geq$ 360	$\geq$ 360	$\geq$ 330	$\geq$ 7,200	$\geq$ 7,000	–	–

[a] Applies if conditions for zone B ("single cropping") are not met.
[b] The program tests if at least one of the crop/LUTs is agro-climatically suitable in the respective grid-cell.

LGP	Length of growing period, i.e., number of days when temperature and soil moisture permit crop growth
$\text{LGP}_{t=5}$	Number of days with mean daily temperatures above 5°C
$\text{LGP}_{t=10}$	Number of days with mean daily temperatures above 10°C
$\text{TS}_{t=0}$	Accumulated temperature (degree-days) on days when mean daily temperature $\geq 0°\text{C}$
$\text{TS}_{t=10}$	Accumulated temperature (degree-days) on days when mean daily temperature $\geq 10°\text{C}$
$\text{TS-G}_{t=5}$	Accumulated temperature during growing period when mean daily temperature $\geq 5°\text{C}$
$\text{TS-G}_{t=10}$	Accumulated temperature during growing period when mean daily temperature $\geq 10°\text{C}$

Tables 4.11 and *4.12* summarize the delineation criteria for multiple cropping zones under rain-fed conditions in the tropics and the subtropics/temperate zones, respectively.

4.8 Review of Results

4.8.1 Stepwise review of suitability analysis procedures

Crop suitability is a result of both agro-climatic and agro-edaphic evaluation. Since agro-climatic ratings are independent of soil limitations and edaphic ratings do not consider climate limitations, the two components must be combined. Therefore, the results of the agro-climatic suitabilities are successively modified, according to edaphic suitabilities, to provide overall crop suitability.

The calculation procedures have been grouped into five steps:

1. Climate data analysis;
2. Crop-specific agro-climatic assessment and potential biomass calculation;
3. Application of agro-climatic constraints;
4. Edaphic assessments;
5. Various applications (e.g., calculation of land with cultivation potential).

Step 1 calculates and organizes climate-related parameters for each grid-cell, i.e.,

- Altitude
- Latitudinal climate
- Presence of cold break
- Continentality index
- Mean annual temperature
- Mean annual minimum temperature
- Mean annual maximum temperature
- Temperature profile: number of days in intervals of 5°C-steps from $<$ –5°C to $>$ 30°C separately for periods of increasing and decreasing temperatures
- Thermal growing periods: number of days > 0°C, > 5°C, > 10°C
- Begins and ends of thermal growing periods
- Accumulated temperature during thermal growing periods
- Mean temperature during thermal growing periods
- Aridity index (precipitation over reference evapotranspiration)
- Aridity index during growing period
- Total number of growing period days
- Number of growing period days when full crop water requirements of reference crop are met
- Total number of wet days, i.e., growing period days with excess moisture
- Number of growing periods
- Begin and end of dormancy period
- Length of individual LGPs
- Number of days in each LGP when crop water requirements can be fully met.
- Number of days in each LGP with excess moisture
- Begin and end dates of each LGP
- Temperature profile during growing period
- Accumulated temperatures (above 0°C, 5°C, 10°C) during growing period
- Average temperature during growing period
- Multiple-cropping zones classification for rain-fed and irrigated conditions

Since all the above data is organized by grid-cell, maps of each item can be produced for spatial verification.

In *Step 2*, all the 154 LUTs (148 crop/LUTs and 6 grass/pasture legume LUTs) are "grown." The LUTs are tested starting successively each day during the permissible window of time (separately determined for irrigated and rain-fed conditions). The highest obtained yield defines the optimal crop calendar of each LUT in each grid-cell. The CROPWAT methodology (FAO, 1992a) is used to calculate crop-specific water balances and to account for yield losses due to water deficits. Calculations are done seven times: once for irrigation conditions, and six times for rain-fed conditions assuming in the soil moisture balance calculations an available water-holding capacity of respectively 150, 125, 100, 75, 50, and 15 mm/m. This provides an understanding of the sensitivity of LGP and crop yield to soil conditions, and permits in the subsequent steps the selection of results corresponding to soil types as specified for a grid cell in the DSMW. The following information is stored for each grid-cell after Step 2:

- Maximum attainable biomass and yield (determined by radiation and temperature)
- Estimated actual crop evapotranspiration (ET_a)
- Accumulated crop water deficit during the growth cycle (i.e., $ET_0 - ET_a$)
- Attainable water-limited biomass and yield

All these individual items can be reproduced in map form, for viewing and for spatial verification.

In *Step 3* specific multipliers are used to reduce yields for what are defined in AEZ as agro-climatic constraints. This step is carried out separately to make the effect of the workability, pest and diseases, and other constraints transparent. The results of Step 3, agro-climatically attainable yields, are stored by crop/LUT for each grid-cell. The intermediate results of agro-climatic suitabilities, therefore, can be mapped for spatial verification.

Step 4 performs the edaphic assessment and combines the agro-climatic results with the soil information. The FAO DSMW, with a grid-cell size of 5-minute latitude/longitude, is used for the assessment, defining soil characteristics (soil type, soil texture, and soil phase) and proportions of different soils in each mapping unit. For terrain-slope conditions, a slope distribution was derived from the 30 arc-seconds GTOPO30 digital elevation database (EROS Data Center, 1998). The slope characterization has been aggregated to the grid-cells of the DSMW in terms of seven classes: 0–2%, 2–5%, 5–8%, 8–16%, 16–30%, 30–45%, and $>$ 45%. Soil and slope rules are applied separately for rain-fed and irrigated conditions. As a result, for each 5-minute grid-cell and each crop/LUT, an expected yield and suitability distribution regarding rain-fed and irrigation conditions are obtained. Suitability is described in five classes: very suitable (VS), suitable (S), moderately suitable (MS), marginally suitable (mS), and not suitable (NS). Results are stored separately for dryland and naturally flooded soils (Fluvisols, and Gleysols with 0–2% slopes). The results have been mapped, and several examples can be found in various Plates on the CD-ROM. An example is presented in Plate D in this report: "Expected grid-cell output per hectare for 120-day rain-fed grain maize (high inputs)." Suitability maps of the single-crop/LUTs have been intensively used for spatial verification.

Step 5. The databases created in steps 1 to 4 have been used to derive additional characterizations and aggregations. Examples follow.

- Calculation of land with cultivation potential involves an aggregation over individual crop/LUTs to estimate how much land is potentially suitable for crop cultivation. Examples of results are presented in Chapter 5 and have proven useful for spatial verification purposes.
- Tabulation of results by ecosystem type: the GLCC 30 arc-seconds data set was aggregated to 11 major ecosystems and subsequently to 5-minute DSMW grid-cells. The resulting ecosystem distribution was matched with the assessed land with cultivation potential in each DSMW grid-cell, providing estimates of suitable extents under current ecosystems. This information proved useful in comparing and verifying, for example, the overlap between potential cultivable land and land shown as being currently in use for cropping.
- Quantification of climatic production risks by using historical time series of suitability results. For each crop/LUT and grid-cell, information was generated on average crop yield, number of crop failures, standard deviation of expected yields, and ratio of average yield versus yield of average climate. In this way the spatial distribution of climatic production risk can be mapped and verified.

As discussed above, the structure of the suitability analysis procedures allows stepwise review of results. As an example of a verification sequence, a selection of intermediate results in map form for 120-day grain maize, grown under rain-fed conditions at high input level, is presented on the CD-ROM:

Plate 14 (Step 1)	Number of growing period days
Plate 15 (Step 2)	Temperature and radiation limited yield for 120-day rain-fed grain maize (high level of inputs)
Plate 16 (Step 2)	Temperature and radiation and water limited yield for 120-day rain-fed grain maize (high level of inputs)
Plate 17 (Step 3)	Agro-climatically attainable yield for 120-day rain-fed grain maize (high level of inputs)
Plate 18 (Step 4)	Expected grid-cell output per hectare for 120-day rain-fed grain maize (high level of inputs)
Plate 19 (Step 5)	Expected grid-cell output per hectare across all 13 rain-fed grain-maize types (high level of inputs)

The results, obtained after completion of each of the above steps, have been used in the process of checking and validating the proper functioning of the various procedures. The intermediate and final results have been helpful for the verification against research data, crop statistics, expert knowledge, etc.

4.8.2 Confirmation of results

Various modes have been pursued for "ground-truthing" and verifying results of the AEZ suitability analysis. Apart from consulting expert knowledge and agricultural research institutes, results have been systematically compared with research data and agricultural statistics. In particular the following activities have been conducted intensively by IIASA and staff of FAO's Economic and Social Department and its Agricultural Department.

- Confirmation of estimated potential crop distribution and yields against quantitative and qualitative occurrence of these crops in national and subnational agricultural statistics.
- Comparison of limits of AEZ potential crop distribution with limits to actual distribution of agricultural land (e.g., by comparison with spatial land use/land cover databases and crop distribution maps).

It should, however, be understood that in the light of improved knowledge, any part of the GAEZ suitability procedures and the model parameters will be scrutinized and may be subject to updating by FAO and IIASA. Also, the model and model parameters are expected to benefit from refinement as a result of follow-up applications.

Notes

[1] The calculated biomass and yields are used to formulate indicative yield ranges for each of the five suitability classes employed at each of the three input circumstances.

[2] Only in cases where conclusive data on crop temperature requirements are available could a distinction be made between optimal and suboptimal conditions.

[3] Fluvisols are by definition flooded by rivers. Fluvisols are young soils where sedimentary structures are clearly recognizable in the soil profile.

[4] Gleysols are generally not flooded by rivers. However, the soil profiles indicate regular occurrence of high groundwater tables through reduction (gley) features. Low-lying Gleysols may be ponded/water-logged by high groundwater and rainfall during the rainy season.

5

Results

The GAEZ assessment provides a comprehensive and spatially explicit database of crop production potential and related factors. The results are a valuable source of information and input to various global and regional applications. Examples of different types of results generated by GAEZ are presented in the various sections of this chapter.

Section 5.1 provides data on occurrence and spatial distribution of climate, soil, and terrain constraints to rain-fed crop production. Section 5.2 presents various results of the crop suitability analyses for rain-fed conditions and for rain-fed and/or irrigated conditions combined. Crop yields are discussed in Section 5.3, in relation to differences between maximum attainable yields and long-term achievable yields. In Section 5.4 we present estimates of land with cultivation potential based on all cereal and non-cereal food and fiber crop/LUTs considered (i.e., from the list of 154 LUTs we excluded banana, oil palm, olives, silage maize, alfalfa, fodder legumes, and grasses).

Section 5.5 highlights areas with high potential for irrigated crops vis-à-vis rain-fed crops. Furthermore, the production potential results are used in Section 5.6 to identify, for individual grid-cells, a "best" cereal in terms of agronomic suitability, food energy and gross value, respectively. Section 5.7 provides estimates of land productivity potential including multi-cropping. Section 5.8 deals with the comparison of estimated crop production potentials and land cover data. Finally, Section 5.9 discusses the sensitivity of regional crop production potential to climate change and Section 5.10 presents examples of impacts of modeled climate change on cereal production. Results of the suitability analysis for a number of temperature and rainfall sensitivity scenarios and GCM-based scenarios are presented.

5.1 Climate, Soil, and Terrain Constraints to Rain-Fed Crop Production

The classifications of soil and terrain constraints in GAEZ for the application with FAO's DSMW have been introduced in Section 3.3. Climate constraints are classified according to length of periods with cold temperatures and moisture limitations. Temperature constraints are related to the length of the temperature growing period LGP$_{t=5}$, i.e., the number of days with mean daily temperature above 5°C. An LGP$_{t=5}$ of less than 120 days is considered a severe constraint, while an LGP$_{t=5}$

Table 5.1. Severe environmental constraints[a] for rain-fed crop production.

Region	Total land (10^6 ha)	Land with severe constraints for rain-fed cultivation of crops: Total with constraints (10^6 ha)	(%)	Too cold (%)	Too dry (%)	Too steep (%)	Poor soils (%)
North America	2,138.5	1,774.7	83.0	35.9	13.9	10.4	69.3
Eastern Europe	171.0	68.0	39.8	0.0	0.0	5.9	38.7
Northern Europe	172.5	135.5	78.5	18.0	0.0	9.9	77.8
Southern Europe	131.6	63.6	48.3	0.7	0.1	31.0	44.3
Western Europe	109.5	56.9	51.9	0.6	0.0	13.5	49.4
Russian Federation	1,674.1	1,412.5	84.4	44.6	2.5	11.9	82.8
Central America & Caribbean	271.7	200.5	73.8	0.0	28.8	25.4	60.3
South America	1,777.6	1,251.8	70.4	0.5	10.6	7.5	63.6
Oceania & Polynesia	849.7	731.2	86.1	0.1	57.6	3.3	61.5
Eastern Africa	639.5	404.7	63.3	0.0	18.5	10.2	53.5
Middle Africa	657.1	515.0	78.4	0.0	13.1	3.3	72.6
Northern Africa	794.1	728.2	91.7	0.0	77.4	5.2	62.7
Southern Africa	266.4	210.6	79.0	0.0	56.9	14.4	43.1
Western Africa	633.0	469.2	74.1	0.0	50.9	0.8	50.5
Western Asia	433.0	382.6	88.4	0.0	74.5	16.4	53.3
Southeast Asia	444.5	271.8	61.2	0.0	0.0	21.7	57.4
South Asia	671.8	475.4	70.8	2.5	33.7	22.8	57.9
East Asia & Japan	1,149.5	933.2	81.2	16.1	32.7	26.8	62.8
Central Asia	414.4	382.0	92.2	2.5	78.4	10.0	78.1
Developing	8,171.5	6,235.5	76.3	2.7	34.4	12.8	60.9
Developed	5,228.0	4,231.8	80.9	29.6	15.8	10.2	70.7
World total	13,399.5	10,467.3	78.1	13.2	27.1	11.8	64.7

[a] Extents of different constraint types do not sum to 100 as the occurrence of constraints may overlap.

of less than 180 days is considered as posing a moderate constraint to crop production. Hyper-arid and arid moisture regimes (LGP $<$ 60 days) are considered severe constraints, and dry semi-arid moisture regimes (LGP 60–119 days) are moderate constraints.

On the basis of currently available soil, terrain, and climatic data, the GAEZ assessment estimates that some 10.5 billion ha of land, i.e., almost four-fifths of the global land surface (excluding Antarctica), suffer rather severe constraints for rain-fed crop cultivation. An estimated 13% is too cold, 27% is too dry, 12% is too steep, and some 65% has poor soil conditions. Note that percentages do not sum up to 100, because several constraints coincide in some locations. *Table 5.1* presents the regional distribution of different types of severe constraints, mostly inhibiting rain-fed crop production.

Table 5.2 gives an account of various kinds of land constraints for rain-fed crop production. The analysis concludes that only 3.5% of the land surface can be regarded to be entirely free of constraining factors. Only for some sub-regions in Europe the share of essentially constraint-free conditions reaches 20% and more. Spreadsheet 1 (CD-ROM) presents results aggregated by broad LGP classes separately, by 22 regions (see Plate 69 [CD-ROM] for the 22 regions). Plates E and F (in this report) show the respective geographical distributions of climatic and of climatic, soil, and terrain constraints combined. Plates 20–28 (CD-ROM) show geographical distributions of the constraints presented in *Table 5.2*.

5.2 Crop Suitability

5.2.1 Rain-fed crops

A total of 154 crop/LUTs were assessed, each at three defined levels of inputs and management. They cover 24 crops, six pasture types, and one fodder legume. The 154 LUTs are listed in *Table 4.1* at the beginning of Chapter 4. The results show that, for wheat, some 6.9% of the total land area is suitable (VS+S+MS) for rain-fed cultivation at a high level of inputs. In developed countries this is 12.8%, and in developing countries only some 3%. For maize the situation is reversed. In developing countries, 11.4% is assessed as suitable, while in developed countries the suitable area is only 5%. Globally, almost 1.2 billion ha (i.e., about 9%) is suitable for grain maize. Results of the crop suitability analysis have been summarized in tabular and map form. *Tables 5.3* and *5.4* present examples of results in terms of *gross*[1] extents of land with cultivation potential for rain-fed production of wheat and grain maize, respectively, under high level of inputs. Spreadsheets 2, 3, and 4 (CD-ROM) include country and regional results of wheat and grain maize under high, intermediate, and low levels of inputs.

Plates 29 and 30 (CD-ROM) present suitability maps of rain-fed production at the high level of inputs for wheat and grain maize. In these maps, the results for each 5-minute latitude/longitude grid-cell of the FAO DSMW are represented by a suitability index SI, which reflects the suitability make-up of a grid-cell in accordance with the definition of suitability classes in AEZ, namely as:

$$SI = VS * 0.9 + S * 0.7 + MS * 0.5 + mS * 0.3\ .$$

Plate G (in this report) presents a suitability index map for rain-fed cereals[2] at the high level of inputs. The algorithm examines in each grid-cell all the crop types belonging to a particular crop group. Among these it determines the LUT that maximizes agronomic suitability. Spreadsheets 2, 3, and 4 (CD-ROM) summarize *gross* extents of land with cultivation potential for six crop groups under rain-fed

Table 5.2. Climate, soil, and terrain constraints for rain-fed crop production, world totals, in 10^6 ha.

Constraints			LGP 0 days CC[a]	LGP 1-59 days CC	LGP 60-119 days C[a]	LGP 120-179 days	LGP 180-269 days	LGP 270-365 days	LGP 365+ days C	Total (10^6 ha)	Total (%)
Temperature	$\mathrm{LGP}_{t=5} > 180$		2,366.0	987.8	1,011.3	984.3	2,202.0	2,109.6	268.0	9,929.0	74.1
	$\mathrm{LGP}_{t=5} < 180$	C	66.7	124.3	181.1	1,331.2	0.0	0.0	0.0	1,703.3	12.7
	$\mathrm{LGP}_{t=5} < 120$	CC	319.9	257.0	1,190.3	0.0	0.0	0.0	0.0	1,767.2	13.2
Terrain	0–8%		1,723.8	759.8	1,072.5	1,165.8	1,127.4	1,235.2	160.8	7,245.3	54.1
slopes	8–16%	C	489.0	245.2	429.0	454.3	409.4	317.2	33.0	2,377.1	17.7
	16–30%	C	354.6	196.0	480.4	419.5	395.6	313.6	42.0	2,201.7	16.4
	$> 30\%$	CC	185.2	168.2	400.7	276.0	269.6	243.6	32.2	1,575.5	11.8
Soil depth	Deep		1,597.2	952.5	1,584.8	1,776.0	1,833.7	1,857.5	242.2	9,843.9	73.5
	Medium	C	120.8	28.0	30.2	27.5	20.8	9.4	3.6	240.3	1.8
	Shallow	CC	421.0	225.3	654.3	449.4	294.2	206.2	20.5	2,270.7	16.9
Soil fertility	High		1,264.6	632.0	742.0	601.0	598.9	310.5	20.3	4,169.2	31.1
	Medium	C	182.9	133.7	314.3	611.4	809.8	827.7	125.4	3,005.3	22.4
	Low	CC	691.4	440.1	1,213.0	1,040.5	740.0	934.8	120.6	5,180.5	38.7
Soil drainage	Good		2,104.7	1,130.7	1,967.2	1,971.0	1,863.7	1,787.1	232.8	11,057.2	82.5
	Poor	CC	34.2	75.1	302.1	281.9	285.0	285.9	33.5	1,297.7	9.7
Soil texture	Medium/fine		1,111.7	795.7	1,596.7	1,620.6	1,597.0	1,753.7	247.8	8,723.2	65.1
	Sandy/stony	CC	307.6	135.0	244.7	179.5	124.6	73.5	5.9	1,070.8	8.0
	Cracking clay	C	719.6	275.1	427.9	452.7	427.2	245.9	12.6	2,561.0	19.1
Soil chemical	None		1,906.2	957.9	2,102.3	2,160.4	2,092.6	2,039.9	263.9	11,523.3	86.0
constraints	S/S/G[b]	CC	232.7	247.9	167.0	92.4	56.1	33.2	2.4	831.7	6.2
Miscellaneous land units		CC	613.6	163.4	113.4	62.7	53.3	36.5	1.7	1,044.5	7.8
Total *without* constraints			0.0	0.0	0.0	134.6	226.4	108.4	0.0	469.4	3.5
Total with *moderate* constraints		C	0.0	0.0	527.9	541.8	672.1	617.8	103.2	2,462.8	18.4
Total with *severe* constraints		CC	2,752.6	1,369.2	1,854.7	1,639.2	1,303.5	1,383.4	164.7	10,467.3	78.1
Total	(10^6 ha)		2,752.6	1,369.2	2,382.7	2,315.6	2,202.0	2,109.6	268.0	13,399.5	100.0
	(%)		20.5	10.2	17.8	17.3	16.4	15.7	2.0	100.0	

[a]C: Moderate or slight constraint. CC: Severe constraint. [b]Salinity/sodicity/gypsum. *Notes:* Individual constraints are non-additive, i.e., they may overlap. In areas with 365-day temperature growing periods, LGP 0 days is referred to as a hyper-arid moisture regime, LGP 1-59 days as arid, LGP 60-119 days as dry semi-arid, LGP 120-179 days as moist semi-arid, LGP 180-269 as subhumid, LGP 270-365 days as humid, and LGP 365+ as per-humid regime.

Table 5.3. Gross extents with cultivation potential for rain-fed wheat by region, high input level.

Region	Total land[a] (10^6 ha)	VS (10^6 ha)	S (10^6 ha)	MS (10^6 ha)	VS+S+MS[b] (%)	mS (10^6 ha)	VS+S+MS+mS (%)	NS (10^6 ha)	NS (%)
North America	2,138.5	52.3	137.6	83.4	12.8	40.7	14.7	1,824.4	85.3
Eastern Europe	171.0	17.5	42.1	29.4	52.0	22.4	65.1	59.6	34.9
Northern Europe	172.5	3.4	21.6	13.5	22.3	8.8	27.4	125.3	72.6
Southern Europe	131.6	6.4	8.2	6.0	15.7	2.7	17.7	108.3	82.3
Western Europe	109.5	16.8	20.4	10.2	43.2	7.4	50.0	54.8	50.0
Russian Federation	1,674.1	20.8	54.4	92.6	10.0	50.5	13.0	1,455.9	87.0
Central America & Caribbean	271.8	1.4	2.2	1.8	2.0	1.2	2.4	265.1	97.6
South America	1,777.6	25.7	44.2	40.8	6.2	32.7	8.1	1,634.1	91.9
Oceania & Polynesia	849.7	4.5	10.1	13.0	3.2	9.9	4.4	812.2	95.6
Eastern Africa	639.5	5.8	12.1	11.7	4.6	7.7	5.8	602.2	94.2
Middle Africa	657.0	0.2	1.0	2.7	0.6	2.0	0.9	651.2	99.1
Northern Africa	794.1	0.3	1.6	2.0	0.5	1.3	0.7	788.9	99.3
Southern Africa	266.4	0.4	0.9	1.1	0.9	0.6	1.1	263.4	98.9
Western Africa	633.0	0.0	0.0	0.0	0.0	0.0	0.0	632.9	100.0
Western Asia	433.0	0.7	3.4	6.4	2.4	3.4	3.2	419.1	96.8
Southeast Asia	444.5	0.2	2.7	4.5	1.6	4.1	2.6	433.0	97.4
South Asia	671.8	0.2	1.6	4.9	1.0	5.1	1.8	660.0	98.2
East Asia & Japan	1,149.5	4.9	30.9	33.4	6.0	16.5	7.5	1,063.7	92.5
Central Asia	414.4	0.5	0.6	4.2	1.3	2.7	1.9	406.3	98.1
Developing	8,171.5	38.1	98.9	111.9	3.0	76.8	4.0	7,846.0	96.0
Developed	5,228.0	123.8	297.0	249.9	12.8	142.9	15.6	4,414.5	84.4
World total	13,399.5	161.8	395.8	361.8	6.9	219.6	8.5	12,260.5	91.5

[a]Total extent derived from digital version of the Soil Map of the World (FAO, 1995c).
[b]VS = very suitable; S = suitable; MS = moderately suitable; mS = marginally suitable; NS = not suitable.

Table 5.4. Gross extents with cultivation potential for rain-fed grain maize by region, high input level.

Region	Total land (10^6 ha)	VS (10^6 ha)	S (10^6 ha)	MS (10^6 ha)	VS+S+MS[a] (%)	mS (10^6 ha)	VS+S+MS+mS (%)	NS (10^6 ha)	NS (%)
North America	2,138.5	17.3	61.4	95.9	8.2	56.6	10.8	1,907.3	89.2
Eastern Europe	171.0	0.0	4.2	18.6	13.4	22.0	26.2	126.1	73.8
Northern Europe	172.5	0.0	0.0	0.0	0.0	0.0	0.0	172.5	100.0
Southern Europe	131.6	0.9	2.1	3.1	4.6	2.1	6.3	123.4	93.7
Western Europe	109.5	0.0	1.7	5.5	6.6	4.6	10.9	97.6	89.1
Russian Federation	1,674.1	0.0	3.5	6.3	0.6	15.6	1.5	1,648.7	98.5
Central America & Caribbean	271.8	4.6	6.1	7.5	6.7	20.1	14.1	233.5	85.9
South America	1,777.6	21.1	74.9	94.0	10.7	193.1	21.6	1,394.4	78.4
Oceania & Polynesia	849.7	6.4	14.0	16.5	4.3	27.2	7.5	785.5	92.5
Eastern Africa	639.5	45.6	62.1	54.3	25.3	42.3	32.0	435.1	68.0
Middle Africa	657.0	30.6	30.2	38.6	15.1	90.2	28.9	467.5	71.1
Northern Africa	794.1	33.5	16.3	12.4	7.8	11.9	9.3	719.9	90.7
Southern Africa	266.4	0.3	1.6	3.3	1.9	7.2	4.6	254.1	95.4
Western Africa	633.0	26.7	38.7	35.1	15.9	42.8	22.6	489.7	77.4
Western Asia	433.0	0.0	0.0	0.0	0.0	0.0	0.0	433.0	100.0
Southeast Asia	444.5	0.4	14.5	22.4	8.4	45.2	18.6	362.0	81.4
South Asia	671.8	38.5	76.4	47.6	24.2	30.0	28.7	479.3	71.3
East Asia & Japan	1,149.5	19.8	37.3	41.5	8.6	22.3	10.5	1,028.7	89.5
Central Asia	414.4	0.1	0.1	0.2	0.1	0.4	0.2	413.7	99.8
Developing	8,171.5	219.6	356.3	355.6	11.4	509.5	17.6	6,730.4	82.4
Developed	5,228.0	26.1	88.9	147.1	5.0	124.3	7.4	4,841.7	92.6
World total	13,399.5	245.7	445.2	502.7	8.9	633.7	13.6	11,572.2	86.4

[a] VS = very suitable; S = suitable; MS = moderately suitable; mS = marginally suitable; NS = not suitable.

conditions, by country and regions, at high, intermediate, and low level inputs, respectively.

For example, for rain-fed cereal food crops at the intermediate input level, we estimate about 2.5 billion ha of gross extents of land to be potentially suitable (VS+S+MS). Of these, some 1.6 billion ha are assessed as very suitable or suitable (VS+S) for at least one cereal type. In other words, about 18.7% of the Earth's terrestrial surface is adjudged to have cultivation potential for cereal crops. As pointed out above, these estimates are termed "gross" extents as they do not include specific allowances for other land uses. An interpretation of how much of these potentially suitable areas would actually be available for cereal production is more difficult to achieve. This will be discussed later on.

For other crop groups, the estimates of gross extents with cultivation potential of (VS+S+MS) and (VS+S) areas, respectively, are as follows: roots and tubers, 1.5 billion ha and 0.8 billion ha; pulses 1.5 billion ha and 0.7 billion ha; oil crops 2.0 billion ha and 1.1 billion ha; sugar crops 0.9 billion ha and 0.4 billion ha; and cotton 0.6 billion ha and 0.3 billion ha.

5.2.2 Rain-fed and/or irrigated crops

The GAEZ model permits the assessment of potential crop suitability for the combination of rain-fed and irrigated crop cultivation. The results have been used to highlight regions where the availability of irrigation facilities would result in substantial increases of potential production and areas with cultivation potential. For the assessment of irrigated land productivity potentials, it has been assumed that (i) water resources of good quality are available, and (ii) irrigation infrastructure is in place. In other words, the assessment identifies areas where climate, soils, and terrain permit irrigated crop cultivation but does not undertake to quantify water availability within a watershed. However, suitability in hyper-arid (LGP $= 0$ days) and arid regions (LGP < 60 days) was limited to specific soil conditions, such as Fluvisols and Gleysols in flat terrain conditions.

Table 5.5 shows the estimated percentage of the Earth's terrestrial surface that is considered suitable for the six crop groups, under respectively rain-fed conditions and for rain-fed plus irrigation conditions. For the intermediate level of inputs, the estimates include very suitable, suitable, and moderately suitable areas (VS+S+MS). At the high level of inputs, very suitable and suitable extents (VS+S) are accounted for. The results for the intermediate level of inputs indicate that irrigation could increase the extents of land with cultivation potential for staple food crops (cereals, roots and tubers, pulses, oil crops) by some 7% to 12%. Larger relative improvements from irrigation would result for sugar crops (almost 40%) and cotton (more than 20%). The potential contribution from irrigation becomes more pronounced when looking at the prime suitability classes, i.e., VS and S, as is done

Table 5.5. Percentage of global land surface potentially suitable for crop production.

	Rain-fed cultivation potential		Rain-fed and/or irrigated cultivation potential	
	High input (% VS+S)	Intermediate input (% VS+S+MS)[a]	High input (% VS+S)	Intermediate input (% VS+S+MS)
Cereals	14.9	18.7	17.0	20.0
Roots & tubers	7.9	11.3	10.4	12.7
Pulses	7.2	11.2	9.7	12.3
Oil crops	10.5	15.2	14.2	16.6
Sugar crops	3.9	6.7	7.8	9.3
Cotton	3.0	4.3	4.6	5.3

[a] VS = very suitable; S = suitable; MS = moderately suitable.

for the high level of inputs. For the four staple food crop groups, the increases in VS+S extents range from about 15% to 35%. For sugar crops the respective area nearly doubles, and for cotton, about 50% more land is assessed as very suitable or suitable.

The extents with cultivation potential for rain-fed and/or irrigated wheat, grain maize and wetland rice at high level of inputs are given in *Tables 5.6–5.8*. Spreadsheets 2 and 3 (CD-ROM) present results for high and intermediate levels of inputs by country and region.

Plates 37, 38, and 39 (CD-ROM) present – for wheat, grain maize and wetland rice under rain-fed and/or irrigated conditions – suitability maps at the high level of inputs. For wheat, 1.2 billion ha and for maize, 1.4 billion ha – about 9% and 11% of the global land surface, respectively – are assessed as very suitable, suitable, or moderately suitable at high level of inputs. For both crops, consideration of irrigation increases the extents of VS+S land by about 45%, whereas the VS+S+MS areas increase less, namely by about 20% for grain maize and about 30% for wheat. For wheat, the VS+S estimates under rain-fed and rain-fed plus irrigated conditions are 558 and 825 million ha, respectively; for grain maize we obtained 691 and 994 million ha, respectively.

Areas suitable for major crop groups are displayed in Plates 40–45 (CD-ROM), which present suitability maps for the high level of inputs of cereals, roots and tubers, pulses, oil crops, sugar crops, and cotton, respectively. Country and region results are provided in Spreadsheets 2 and 3 (CD-ROM).

5.2.3 Hyper-arid and arid land with cultivation potential under irrigation

Globally, some 3.6 billion ha, i.e., about 27% of the Earth's land surface, are too dry for rain-fed agriculture (see *Table 5.1* at beginning of this chapter). As a working

Table 5.6. Gross extents with cultivation potential for rain-fed and/or irrigated wheat (10^6 ha) by region, high input level.

Region	Total land (10^6 ha)	VS (10^6 ha)	S (10^6 ha)	MS (10^6 ha)	VS+S+MS[a] (%)	mS (10^6 ha)	VS+S+MS+mS (%)	NS (10^6 ha)	NS (%)
North America	2,138.5	110.9	135.1	72.7	14.9	35.9	16.6	1,783.9	83.4
Eastern Europe	171.0	27.9	38.6	26.0	54.1	20.1	65.9	58.3	34.1
Northern Europe	172.5	6.2	19.0	13.3	22.3	8.8	27.4	125.3	72.6
Southern Europe	131.6	9.7	7.8	4.8	17.0	2.4	18.8	106.9	81.2
Western Europe	109.5	22.5	16.9	8.6	43.8	7.4	50.5	54.2	49.5
Russian Federation	1,674.1	38.0	75.5	79.3	11.5	44.5	14.2	1,436.9	85.8
Central America & Caribbean	271.8	1.6	3.7	2.1	2.7	1.2	3.2	263.1	96.8
South America	1,777.6	36.4	48.8	40.0	7.0	31.4	8.8	1,620.9	91.2
Oceania & Polynesia	849.7	20.3	23.6	13.0	6.7	8.2	7.7	784.5	92.3
Eastern Africa	639.5	7.7	22.1	16.3	7.2	7.6	8.4	585.8	91.6
Middle Africa	657.0	1.1	4.7	4.8	1.6	2.0	1.9	644.4	98.1
Northern Africa	794.1	3.9	12.5	3.9	2.6	1.2	2.7	772.7	97.3
Southern Africa	266.4	1.2	5.8	2.2	3.4	0.6	3.6	256.7	96.4
Western Africa	633.0	0.4	2.1	0.3	0.4	0.0	0.4	630.3	99.6
Western Asia	433.0	3.3	7.1	6.2	3.8	3.1	4.5	413.3	95.5
Southeast Asia	444.5	0.2	3.0	4.7	1.8	4.1	2.7	432.5	97.3
South Asia	671.8	0.8	30.9	15.2	7.0	4.8	7.7	620.1	92.3
East Asia & Japan	1,149.5	11.7	49.8	39.0	8.7	16.4	10.2	1,032.6	89.8
Central Asia	414.4	6.6	7.5	5.2	4.7	2.4	5.2	392.7	94.8
Developing	8,171.5	72.8	195.6	137.9	5.0	74.2	5.9	7,691.0	94.1
Developed	5,228.0	237.5	319.0	219.7	14.8	127.8	17.3	4,324.0	82.7
World total	13,399.5	310.3	514.6	357.6	8.8	202.0	10.3	12,015.1	89.7

[a] VS = very suitable; S = suitable; MS = moderately suitable; mS = marginally suitable; NS = not suitable.

Table 5.7. Gross extents with cultivation potential for rain-fed and/or irrigated grain maize by region, high input level.

Region	Total land[a] (10^6 ha)	VS (10^6 ha)	S (10^6 ha)	MS (10^6 ha)	VS+S+MS[b] (%)	mS (10^6 ha)	VS+S+MS+mS (%)	NS (10^6 ha)	NS (%)
North America	2,138.5	69.8	80.4	68.6	10.2	42.6	12.2	1,877.2	87.8
Eastern Europe	171.0	1.6	9.8	20.3	18.5	20.1	30.3	119.2	69.7
Northern Europe	172.5	0.0	0.0	0.0	0.0	0.0	0.0	172.5	100.0
Southern Europe	131.6	3.8	5.9	2.4	9.2	1.4	10.2	118.2	89.8
Western Europe	109.5	0.3	3.7	6.1	9.1	4.5	13.2	95.1	86.8
Russian Federation	1,674.1	2.0	9.6	9.9	1.3	15.1	2.2	1,637.5	97.8
Central America & Caribbean	271.8	7.0	7.5	7.1	7.9	19.2	15.0	231.0	85.0
South America	1,777.6	48.9	80.7	83.2	12.0	184.4	22.3	1,380.4	77.7
Oceania & Polynesia	849.7	35.9	26.2	14.2	9.0	14.1	10.6	759.4	89.4
Eastern Africa	639.5	58.0	66.9	52.6	27.8	39.0	33.9	422.9	66.1
Middle Africa	657.0	33.1	31.2	36.9	15.4	89.3	29.0	466.6	71.0
Northern Africa	794.1	53.1	21.6	11.2	10.8	9.5	12.0	698.8	88.0
Southern Africa	266.4	5.5	2.3	2.4	3.8	5.6	5.9	250.6	94.1
Western Africa	633.0	33.5	42.7	33.8	17.4	40.0	23.7	483.0	76.3
Western Asia	433.0	7.2	3.7	0.5	2.6	0.0	2.6	421.6	97.4
Southeast Asia	444.5	0.4	14.6	22.5	8.4	45.0	18.6	362.0	81.4
South Asia	671.8	53.7	83.0	41.3	26.5	24.0	30.1	469.8	69.9
East Asia & Japan	1,149.5	30.7	47.0	37.2	10.0	20.1	11.7	1,014.5	88.3
Central Asia	414.4	6.3	6.6	1.7	3.5	0.3	3.6	399.5	96.4
Developing	8,171.5	336.0	405.9	329.2	13.1	480.3	19.0	6,620.1	81.0
Developed	5,228.0	114.7	137.4	122.6	7.2	93.8	9.0	4,759.6	91.0
World total	13,399.5	450.7	543.3	451.8	10.8	574.1	15.1	11,379.7	84.9

[a]VS = very suitable; S = suitable; MS = moderately suitable; mS = marginally suitable; NS = not suitable.

Table 5.8. Gross extents with cultivation potential for rain-fed and/or irrigated wetland rice by region, high input level.

Region	Total land (10^6 ha)	VS (10^6 ha)	S (10^6 ha)	MS (10^6 ha)	VS+S+MS[a] (%)	mS (10^6 ha)	VS+S+MS+mS (%)	NS (10^6 ha)	NS (%)
North America	2,138.5	57.0	41.0	13.9	5.2	4.0	5.4	2,022.6	94.6
Eastern Europe	171.0	2.6	2.6	1.7	4.0	0.0	4.0	164.1	96.0
Northern Europe	172.5	0.0	0.0	0.0	0.0	0.0	0.0	172.5	100.0
Southern Europe	131.6	5.6	2.5	0.5	6.5	0.0	6.5	123.1	93.5
Western Europe	109.5	0.5	0.2	0.0	0.7	0.0	0.7	108.8	99.3
Russian Federation	1,674.1	1.5	4.0	3.3	0.5	0.5	0.6	1,664.8	99.4
Central America & Caribbean	271.8	8.8	13.8	7422	11.1	1.9	11.7	239.8	88.3
South America	1,777.6	103.6	167.5	152.5	23.8	109.7	30.0	1,244.2	70.0
Oceania & Polynesia	849.7	21.8	29.6	13929	7.7	5.5	8.3	778.8	91.7
Eastern Africa	639.5	25.4	24.6	16.3	10.4	13.4	12.5	559.8	87.5
Middle Africa	657.0	22.1	55.7	63.1	21.4	29.9	26.0	486.3	74.0
Northern Africa	794.1	17.7	26.5	11.0	6.9	5.9	7.7	733.1	92.3
Southern Africa	266.4	5.3	1.3	0.1	2.5	0.0	2.5	259.8	97.5
Western Africa	633.0	11.6	28.2	23.6	10.0	13.6	12.2	556.0	87.8
Western Asia	433.0	6715	2596	0.1	2.2	0.0	2.2	423.6	97.8
Southeast Asia	444.5	18.0	33.9	23.3	16.9	18.8	21.1	350.6	78.9
South Asia	671.8	18.6	54.4	21.8	14.1	9.7	15.6	567.3	84.4
East Asia & Japan	1,149.5	21.9	27.2	13.7	5.5	2.2	5.7	1,084.5	94.3
Central Asia	414.4	4.9	3.4	0.5	2.1	0.0	2.1	405.5	97.9
Developing	8,171.5	264.4	439.1	335.3	12.7	209.4	15.3	6,923.3	84.7
Developed	5,228.0	89.2	79.9	31.3	3.8	5.8	3.9	5,021.8	96.1
World total	13,399.5	353.6	519.0	366.6	9.2	215.2	10.9	11,945.2	89.1

[a] VS = very suitable; S = suitable; MS = moderately suitable; mS = marginally suitable; NS = not suitable.

hypothesis we have only considered for irrigation those soils in hyper-arid (LGP 0 days) and arid (LGP $<$ 1-59 days) zones that indicate possible availability of surface or groundwater resources. These soils are Fluvisols, which by definition are regularly flooded, and Gleysols, which indicate regular occurrence of high groundwater tables.

Assuming availability of water resources, about 64 million ha, i.e., only about 1.8% of these dry zones, were assessed as potentially very suitable and suitable (VS+S) for cereal crops under irrigation. More than 40% of this land, potentially suitable under irrigation, is located throughout Africa. *Table 5.9* presents the estimated extents of irrigable land in hyper-arid (with a moisture growing period of zero days [LGP 0]) and arid (with a moisture growing period of less than sixty days [LGP 1-59]) zones potentially very suitable and suitable for cultivation of cereal crops. Country and regional results are presented in Spreadsheet 5 (CD-ROM). In comparison, FAO reports that about 255 million ha were irrigated globally in 1994–1996. Note, however, that these irrigated lands were distributed among various climatic zones, e.g., humid rice growing areas in Asia, rather than appearing in only hyper-arid and arid regions.

5.3 Crop Yields

Maximum[3] agro-climatically attainable yield ranges were calculated for the tropics, subtropics, and temperate/boreal zones, respectively. *Table 5.10* presents potential yields for irrigated production at high and intermediate levels of inputs. *Table 5.11* lists yield ranges for rain-fed conditions at high, intermediate, and low levels of inputs. The maximum attainable yields for rain-fed conditions represent averages of simulated year-by-year yields attainable during the period 1960 to 1996. The yields are presented in ranges indicating the maximum attainable yields of the least and most productive cultivars for each of the 30 crop species in the tropics, subtropics, and temperate/boreal zones, respectively. Furthermore, the yields given in *Tables 5.10* and *5.11* represent yields attained during the cultivation phase of cultivation-fallow cycles. In low and intermediate input agriculture, fallow and/or crop rotations are needed to maintain the soil nutrient balance and to break pest and disease cycles. The required intensity of fallow depends on crop rotations implemented, on soil characteristics such as soil nutrient availability and nutrient retention capacity, on climatic conditions, and on management and agricultural inputs applied. As a rule of thumb for low level input/management conditions, fallow period requirements may vary between 30–90% of the cultivation fallow cycle. For intermediate level input/management conditions, fallow requirements may vary between 10% and 30% (see *Table 5.19*).

Table 5.9. Gross extents of potentially irrigable land in hyper-arid and arid zones very suitable and suitable (VS+S) for cereals.

Region	Irrigated land in 1994–1996 (10^6 ha)	(A) VS+S rain-fed and irrigated potential (10^6 ha)	Hyper-arid zone (LGP 0 days) VS+S irrigable land (high input)		Arid zone (LGP 1-59 days) VS+S irrigable land (high input)		Hyper-arid and arid zones total VS+S irrigable land (high input)	
			10^6 ha	% of (A)	10^6 ha	% of (A)	10^6 ha	% of (A)
North America	22.1	241.0	1.1	0.5	1.3	0.5	2.4	1.0
Eastern Europe	7.4	64.3	0.0	0.0	0.0	0.0	0.0	0.0
Northern Europe	0.9	22.9	0.0	0.0	0.0	0.0	0.0	0.0
Southern Europe	8.7	17.5	0.0	0.0	0.0	0.0	0.0	0.0
Western Europe	2.7	38.5	0.0	0.0	0.0	0.0	0.0	0.0
Russian Federation	5.2	113.0	0.0	0.0	1.5	1.3	1.5	1.3
Central America & Caribbean	8.0	34.6	0.6	1.8	0.6	1.6	1.2	3.4
South America	9.8	439.1	3.9	0.9	1.3	0.3	5.2	1.2
Oceania & Polynesia	2.8	87.1	0.0	0.0	0.0	0.0	0.0	0.0
Eastern Africa	2.1	150.5	2.3	1.5	2.5	1.6	4.8	3.2
Middle Africa	0.1	173.4	0.2	0.1	0.1	0.1	0.3	0.2
Northern Africa	7.9	84.4	15.1	17.8	1.8	2.1	16.8	19.9
Southern Africa	1.4	9.7	0.2	2.0	0.7	7.4	0.9	9.4
Western Africa	0.8	117.3	3.5	3.0	1.9	1.6	5.3	4.6
Western Asia	11.5	14.2	6.2	43.8	0.7	4.9	6.9	48.7
Southeast Asia	15.3	65.8	0.0	0.0	0.0	0.0	0.0	0.0
South Asia	85.7	158.6	3.4	2.1	1.5	0.9	4.8	3.1
East Asia & Japan	55.5	92.1	4.5	4.8	0.7	0.7	5.1	5.5
Central Asia	12.1	16.2	0.0	0.0	8.3	51.5	8.3	51.5
Developing	207.4	1,353.6	39.8	2.9	20.0	1.5	59.8	4.4
Developed	47.4	586.8	1.1	0.2	2.8	0.5	3.9	0.7
World total	254.8	1,940.4	40.9	2.1	22.8	1.2	63.7	3.3

Table 5.10. Maximum attainable crop yield ranges (t/ha) for high and intermediate level inputs in tropical, subtropical, and temperate environments under irrigated conditions.

	High input yields (t/ha)			Intermediate input yields (t/ha)		
Crop	Tropics	Subtropics	Temperate	Tropics	Subtropics	Temperate
Wheat (hibernating)	n.a.	6.6 – 14.2	7.4 – 13.5	n.a.	4.6 – 10.2	5.2 – 9.7
Wheat (non-hibernating)	5.3 – 11.1	5.4 – 9.9	5.3 – 8.5	3.3 – 7.4	3.4 – 6.9	3.3 – 5.7
Rice (wetland)	7.9 – 12.2	8.7 – 12.7	8.2 – 10.9	6.1 – 9.5	6.5 – 9.9	6.3 – 8.7
Rice (dryland)	4.8 – 6.8	n.a.	n.a.	3.1 – 4.6	n.a.	n.a.
Maize (grain)	6.0 – 15.6	8.5 – 17.1	8.0 – 15.7	3.5 – 10.5	5.3 – 12.2	4.9 – 11.3
Maize (silage)	n.a.	17.0 – 26.0	15.9 – 24.0	n.a.	13.0 – 20.9	12.1 – 19.2
Barley (hibernating)	n.a.	6.6 – 14.2	7.4 – 13.5	n.a.	4.6 – 10.2	5.2 – 9.7
Barley (non-hibernating)	4.7 – 9.9	5.2 – 9.2	3.9 – 7.6	2.9 – 6.7	2.9 – 6.4	2.8 – 5.1
Sorghum	3.4 – 12.1	7.8 – 13.0	5.9 – 10.3	2.2 – 7.5	4.6 – 8.1	3.4 – 6.4
Pearl millet	4.2 – 5.8	n.a	n.a	2.5 – 3.7	n.a.	n.a.
Foxtail millet	n.a.	5.2 – 10.0	5.0 – 9.3	n.a	3.6 – 7.2	3.5 – 6.7
Rye (hibernating)	n.a.	4.2 – 8.3	4.6 – 7.9	n.a	2.9 – 5.9	3.3 – 5.7
Rye (non-hibernating)	n.a.	3.5 – 6.6	3.4 – 6.3	n.a	2.1 – 4.1	2.0 – 3.9
White potato	7.4 – 15.8	8.1 – 16.5	7.8 – 15.2	4.9 – 10.6	5.4 – 11.1	5.2 – 10.2
Sweet potato	7.5 – 15.4	7.5 – 15.9	n.a	5.0 – 10.6	5.0 – 10.9	n.a.
Cassava	16.6	n.a	n.a	11.0	n.a.	n.a.
Phaseolus bean	3.4 – 5.5	3.1 – 5.6	3.0 – 4.8	2.2 – 3.7	2.0 – 3.7	1.9 – 3.2
Chickpea	3.2 – 4.7	3.5 – 6.1	n.a	2.0 – 3.1	2.2 – 4.1	n.a.
Cowpea	2.9 – 4.7	n.a.	n.a.	1.9 – 3.1	n.a.	n.a.
Soybean	3.1 – 4.8	4.6 – 5.5	4.3 – 5.1	2.0 – 3.2	3.0 – 3.6	2.8 – 3.4
Rape	4.5 – 5.6	4.5 – 6.0	4.7 – 5.7	2.6 – 3.5	2.9 – 3.8	2.8 – 3.6
Groundnut	3.1 – 4.7	3.2 – 4.9	3.1 – 4.6	2.0 – 3.1	2.0 – 3.3	2.0 – 3.0
Sunflower	5.6 – 6.7	4.9 – 6.1	4.7 – 5.8	3.9 – 4.8	3.4 – 4.4	3.3 – 4.1
Oil palm	8.7	6.4	n.a.	6.0	4.4	n.a.
Olive	n.a.	6.7	5.4	n.a.	4.1	3.3
Cotton	1.1 – 1.6	1.2 – 1.6	1.2 – 1.5	0.7 – 1.0	0.8 – 1.0	0.7 – 0.9
Sugarcane	21.0	20.1	n.a,	16.5	15.8	n.a.
Sugar beet	n.a.	7.1 – 9.3	6.7 – 8.6	n.a.	4.8 – 6.7	4.6 – 6.2
Banana/Plantain	11.5	11.5	n.a.	8.4	8.4	n.a.
Alfalfa	n.a.	26.7	21.5	n.a	16.9	13.6

Table 5.11. Average of year 1960 – 1996 simulated maximum attainable crop yield ranges (t/ha) for high, intermediate, and low level inputs in tropical, subtropical, and temperate environments under rain-fed conditions.

	High input yields (t/ha)			Intermediate input yields (t/ha)			Low input yields (t/ha)		
Crop	Tropics	Subtropics	Temperate	Tropics	Subtropics	Temperate	Tropics	Subtropics	Temperate
Wheat (hibernating)	n.a.	4.2 – 11.8	5.9 – 12.1	n.a.	2.9 – 8.4	4.1 – 8.7	n.a.	1.6 – 4.3	2.4 – 4.9
Wheat (non-hibernating)	4.5 – 8.5	4.6 – 8.0	4.6 – 7.7	2.8 – 5.7	2.9 – 5.4	2.9 – 5.2	1.2 – 2.7	1.3 – 3.0	1.5 – 2.7
Rice (wetland)	6.2 – 9.9	6.2 – 9.2	6.4 – 8.6	4.8 – 7.7	4.8 – 7.3	4.9 – 6.9	2.9 – 5.0	2.9 – 4.7	3.2 – 4.9
Rice (dryland)	3.5 – 5.5	n.a.	n.a.	2.3 – 3.7	n.a.	n.a.	1.2 – 1.9	n.a.	n.a.
Maize (grain)	4.6 – 12.5	6.3 – 12.3	6.1 – 12.1	2.7 – 8.5	4.0 – 8.9	3.8 – 8.7	1.1 – 5.1	1.8 – 5.8	1.8 – 5.3
Maize (silage)	n.a.	12.6 – 19.2	12.4 – 18.8	n.a.	9.7 – 15.2	9.4 – 15.1	n.a.	6.9 – 12.0	6.7 – 11.1
Barley (hibernating)	n.a.	4.2 – 11.8	5.9 – 12.1	n.a.	2.3 – 8.4	4.1 – 8.7	n.a.	1.6 – 4.3	2.4 – 4.9
Barley (non-hibernating)	4.1 – 7.7	3.0 – 7.3	3.5 – 6.8	2.5 – 5.2	2.2 – 5.1	2.5 – 4.6	1.1 – 2.7	1.1 – 2.8	1.3 – 2.5
Sorghum	2.6 – 9.7	5.8 – 8.7	3.6 – 6.3	1.7 – 6.1	3.4 – 5.5	2.1 – 3.9	0.9 – 2.6	1.5 – 2.4	0.9 – 2.0
Pearl millet	2.7 – 4.7	n.a	n.a	1.6 – 3.0	n.a.	n.a.	0.9 – 1.6	n.a.	n.a.
Foxtail millet	n.a.	3.7 – 7.0	4.1 – 6.8	n.a	2.6 – 5.0	2.5 – 4.9	n.a	1.5 – 2.8	1.4 – 2.7
Rye (hibernating)	n.a.	2.6 – 7.0	3.7 – 7.2	n.a	1.9 – 5.0	2.6 – 5.2	n.a	1.0 – 2.5	1.5 – 3.0
Rye (non-hibernating)	n.a.	2.8 – 5.9	3.0 – 5.7	n.a	1.6 – 3.7	1.8 – 3.6	n.a	0.6 – 1.4	0.8 – 1.6
White potato	5.8 – 11.8	5.4 – 11.6	6.4 – 10.3	3.8 – 8.0	3.6 – 7.8	4.3 – 6.9	2.1 – 4.0	1.9 – 4.1	2.3 – 3.7
Sweet potato	5.2 – 11.8	5.3 – 11.0	n.a	3.5 – 8.1	3.5 – 7.6	n.a.	1.7 – 4.6	1.6 – 4.1	n.a.
Cassava	15.5	n.a	n.a	10.2	n.a.	n.a.	4.1	n.a	n.a
Phaseolus bean	2.8 – 4.2	2.4 – 4.0	2.5 – 3.7	1.8 – 2.8	1.5 – 2.6	1.6 – 2.4	0.9 – 1.3	0.8 – 1.2	0.8 – 1.2
Chickpea	1.9 – 3.1	1.9 – 2.9	n.a	1.2 – 2.2	1.6 – 2.4	n.a.	0.6 – 1.0	0.8 – 1.0	n.a.
Cowpea	2.5 – 3.8	n.a.	n.a.	1.6 – 2.5	n.a.	n.a.	0.7 – 1.2	n.a	n.a
Soybean	2.7 – 3.8	3.4 – 4.2	3.4 – 3.8	1.7 – 2.5	2.2 – 2.8	2.2 – 2.6	0.8 – 1.2	1.0 – 1.2	0.9 – 1.1
Rape	3.7 – 4.4	2.6 – 4.5	3.9 – 4.4	2.2 – 2.8	1.6 – 2.8	2.3 – 3.0	0.9 – 1.3	0.7– 1.1	1.0 – 1.3
Groundnut	2.7 – 3.8	2.6 – 3.5	1.8 – 2.6	1.7 – 2.5	1.7 – 2.4	1.1 – 1.9	0.8 – 1.2	0.8 – 1.2	0.5 – 0.9
Sunflower	4.1 – 4.9	3.4 – 4.0	3.7 – 3.9	2.9 – 3.5	2.3 – 2.9	2.6 – 2.7	1.6 – 2.1	1.4 – 1.7	1.5 – 1.6
Oil palm	7.5	3.7	n.a.	5.2	2.6	n.a.	2.8	1.5	n.a
Olive	n.a.	5.9	4.6	n.a.	3.6	2.8	n.a.	1.7	1.2
Cotton	0.9 – 1.2	0.9 – 1.2	0.5 – 0.6	0.6 – 0.8	0.6 – 0.7	0.4 – 0.5	0.16 – 0.28	0.15 – 0.22	0.12 – 0.16
Sugarcane	17.1	16.0	n.a.	13.4	12.6	n.a.	9.4	8.5	n.a.
Sugar beet	n.a.	5.0 – 6.3	5.4 – 6.0	n.a.	3.9 – 4.7	3.8 – 4.6	n.a.	2.2 – 3.6	2.3 – 2.7
Banana/Plantain	9.7	9.0	n.a.	6.8	6.6	n.a.	3.2	3.3	n.a.
Alfalfa	n.a.	23.8	19.9	n.a	15.1	12.6	n.a.	7.4	6.2

With balanced fertilizer applications and proper pest and disease management (which is best possible at high level of inputs), only limited fallow will be required to maintain soil fertility and to keep pest and disease outbreaks in check. At low level of inputs – assuming virtually no application of chemicals and only limited organic fertilizer, and very limited or no application of biocides – there is a need for considerable fallow periods in the crop rotations to restore soil nutrient status and to break pest and disease cycles (see Appendix XII on CD-ROM). The expected long-term yields as estimated by the GAEZ procedures assume that proper crop/fallow cycles are respected. The yields attained over the long term are therefore well below the estimated maximum attainable yields.

Table 5.12 compares in each grid-cell maximum attainable yields and long-term achievable yields for the best crop among wheat, rice, and grain maize, averaged over all very suitable, suitable, and moderately suitable land (VS+S+MS). The calculations assume the best suitable cereal to be chosen and aggregate yields for 22 regions and each level of inputs (see Section 4.6 for a discussion of fallow period requirements and cultivation factors). Spreadsheet 6 (CD-ROM) provides the same information at the regional and country level.

On average, long-term achievable yields are 10%, 20%, and 55% lower than maximum attainable yields, at high, intermediate, and low levels of inputs, respectively.

5.4 Land with Cultivation Potential

The estimation of the extent of land with cultivation potential for rain-fed crops depends on a variety of assumptions: the range of crop types considered, the definition of what minimum level of outputs qualifies as acceptable, the social acceptance of land-cover conversions (in particular forests), and the assumptions about what land constraints may be alleviated with level of inputs and investment. The results presented in this section are based on the following calculation procedures for each 5-minute grid-cell of the DSMW:

(1) Determine all land very suitable and suitable at high level of inputs for the crops offering the largest total extent;
(2) Of the remaining balance of land after (1), determine all land very suitable, suitable, or moderately suitable at intermediate level of inputs for the crops offering the largest extent;
(3) Of the further balance of land after (1) and (2), determine all suitable land (i.e., very suitable, suitable, moderately suitable, or marginally suitable) at low level of inputs for the crops offering the largest extent.

Table 5.12. Maximum attainable and long-term achievable[a] yields for rain-fed wheat, rice, or grain maize averaged over all VS+S+MS land, by region and level of inputs.

Region	Low inputs		Intermediate inputs		High inputs	
	Short-term attainable (t/ha)	Long-term achievable (t/ha)	Short-term attainable (t/ha)	Long-term achievable (t/ha)	Short-term attainable (t/ha)	Long-term achievable (t/ha)
North America	0.8	0.4	3.6	2.8	5.8	5.2
Eastern Europe	1.1	0.4	4.2	3.3	6.5	5.9
Northern Europe	0.9	0.4	3.7	2.9	5.8	5.2
Southern Europe	0.9	0.3	3.6	2.8	6.3	5.7
Western Europe	1.1	0.3	4.3	3.4	7.0	6.4
Russian Federation	0.7	0.3	2.9	2.5	4.4	4.0
Central America & Caribbean	1.1	0.6	3.7	3.1	5.9	5.4
South America	1.2	0.6	3.6	3.0	5.6	5.1
Oceania & Polynesia	0.7	0.4	3.2	2.6	5.3	4.8
Eastern Africa	1.0	0.4	3.8	3.0	6.9	6.2
Middle Africa	1.2	0.6	3.8	3.1	6.2	5.6
Northern Africa	1.0	0.4	4.1	3.3	7.5	6.8
Southern Africa	0.8	0.4	3.1	2.5	4.7	4.3
Western Africa	1.0	0.4	3.8	3.0	6.7	6.1
Western Asia	0.8	0.4	3.1	2.5	4.5	4.1
Southeast Asia	1.3	0.7	3.7	3.1	5.6	5.1
South Asia	1.1	0.5	4.1	3.3	6.8	6.1
East Asia & Japan	1.0	0.5	3.4	2.8	5.9	5.3
Central Asia	0.7	0.4	3.0	2.5	3.6	3.3
Developing	1.1	0.5	3.7	3.0	6.2	5.6
Developed	0.9	0.4	3.5	2.8	5.6	5.1
World total	1.0	0.4	3.7	3.0	5.9	5.4

[a] Long-term achievable yields are calculated by applying a fallow period requirement factor dependent on climatic conditions, soil type, crop, and level of inputs/management (see Section 4.6).

The total extents obtained in this way for each grid-cell, referred to as *mixed* level of inputs, were calculated for rain-fed and rain-fed plus irrigated conditions. The results have been aggregated to various levels. Country and regional aggregations are presented in Spreadsheet 8 (CD-ROM).

Table 5.13 lists *gross* extents of land with cultivation potential for rain-fed conditions in comparison to levels of cultivated land use in 1994–1996. Note that the extents in this table are termed “gross” since no land was subtracted as is required for nonagricultural uses, e.g., infrastructure, settlements, legally protected areas.

When considering all crop types modeled in GAEZ (excluding silage maize, forage legumes, and grasses) and mixing all three input levels, we conclude that around 22% of the Earth’s land surface (excluding Antarctica) can be regarded as suitable for crop cultivation. In developed regions, almost 19% is land with rain-fed cultivation potential. In developing regions, the amount is about 25%. Noting that the available areas are “gross” rather than “net,” we estimate that the land with cultivation potential is about twice the area that was actually in use for cultivation during 1994–1996 (according to FAOSTAT). Of this land balance, almost 80% occurs in South America and Africa alone. Despite this optimistic aggregate picture, *Table 5.13* points to several regions where the rain-fed cultivation potential has already been exceeded or is nearly fully exhausted. Further details, in terms of suitability classes (including marginally suitable land) by input level, are shown in *Table 5.15*. Plate H in this report (Plate 46 on CD-ROM) shows a map with distribution of rain-fed crop cultivation potential.

By looking at all crop types, without considering the demand for different products, we may well overestimate the *useful* extents of land with cultivation potential. Therefore, *Table 5.14* was compiled by restricting the considered crop types to the three major cereals, namely wheat, rice, and grain maize. Under these assumptions, an estimate of about 2.5 billion ha of land with rain-fed cultivation potential (VS+S+MS) was obtained. Of these, 1.6 billion ha were found in developing countries and 0.9 billion ha in developed countries. Spreadsheet 7 (CD-ROM) presents, by region and country, extents of land in use for crop cultivation (1994–1996) and gross extents of land with potential for rain-fed cultivation (VS+S+MS).

To take yet another look at the crop suitability results, in *Table 5.16* and Spreadsheet 9 (CD-ROM) we present per capita land currently (i.e., average of 1994–1996) in use for cultivation and per capita *net*[4] rain-fed land with cultivation potential for populations in 1995[5] and projected populations in 2050. In the calculations, the population projections of the United Nations medium variant were used (United Nations, 2001). *Table 5.17* presents the same data, but excludes areas either under closed forest (FAO’s Global Forest Resources Assessment 2000) or areas that are legally protected. The protected areas include IUCN classes I-IV, Ramsar (Wetlands) Convention, World Heritage Convention, Biogenetic Reserves, European Diploma Type “A,” and Bird Directive.

Table 5.13. Extents of land in use for crop cultivation (1994–1996)[a] and gross extents of land with potential for rain-fed cultivation (VS+S+MS).

Region	Total land (10^6 ha)	Land in use for crop cultivation (FAOSTAT 1994–1996) A (10^6 ha)	A (%)	VS+S+MS land with rain-fed cultivation potential (mixed inputs) B (10^6 ha)	B (%)	Balance B-A (10^6 ha)	Balance (B-A)/A (%)	Balance (B-A)/B (%)
North America	2,138.5	225.3	10.5	366.3	17.1	141.0	63	38
Eastern Europe	171.0	81.7	47.8	121.9	71.3	40.2	49	33
Northern Europe	172.5	21.6	12.5	43.8	25.4	22.2	103	51
Southern Europe	131.6	45.6	34.7	46.5	35.3	0.8	2	2
Western Europe	109.5	35.1	32.1	64.2	58.6	29.1	83	45
Russian Federation	1,674.1	130.1	7.8	225.9	13.5	95.8	74	42
Central America & Caribbean	271.8	43.5	16.0	58.8	21.6	15.3	35	26
South America	1,777.6	114.8	6.5	669.2	37.6	554.4	483	83
Oceania & Polynesia	849.7	53.2	6.3	101.8	12.0	48.6	91	48
Eastern Africa	639.5	46.0	7.2	240.9	37.7	194.9	424	81
Middle Africa	657.1	24.8	3.8	270.3	41.1	245.5	991	91
Northern Africa	794.1	44.1	5.6	94.0	11.8	49.8	113	53
Southern Africa	266.4	17.4	6.5	28.8	10.8	11.3	65	39
Western Africa	633.0	65.4	10.3	178.6	28.2	113.2	173	63
Western Asia	433.0	46.1	10.6	31.7	7.3	–14.3	–31	–45
Southeast Asia	444.5	89.6	20.2	102.0	22.9	12.4	14	12
South Asia	671.8	231.6	34.5	196.0	29.2	–35.6	–15	–18
East Asia & Japan	1,149.5	144.1	12.5	144.8	12.6	0.7	1	1
Central Asia	414.4	45.2	10.9	15.5	3.7	–29.7	–66	–192
Developing	8,171.5	909.6	11.1	2,024.7	24.8	1,115.1	123	55
Developed	5,228.0	595.5	11.4	976.1	18.7	380.5	64	39
World total	13,399.5	1,505.2	11.2	3,000.8	22.4	1,495.7	99	50

[a] *Source:* FAOSTAT, Rome.

Table 5.14. Extents of land in use for crop cultivation (1994–1996)[a] and gross extents of land with potential for rain-fed wheat, grain maize, or rice cultivation (VS+S+MS).

Region	Total land (10^6 ha)	Land in use for crop cultivation (FAOSTAT 1994–1996) A (10^6 ha)	A (%)	Land suitable for rain-fed cereals (VS+S+MS) (mixed inputs) B (10^6 ha)	B (%)	Balance B-A (10^6 ha)	Balance (B-A)/A (%)	Balance (B-A)/B (%)
North America	2,138.5	225.3	10.5	347.3	16.2	122.0	54	35
Eastern Europe	171.0	81.7	47.8	114.3	66.9	32.6	40	29
Northern Europe	172.5	21.6	12.5	39.6	22.9	18.0	84	46
Southern Europe	131.6	45.6	34.7	45.3	34.4	-0.3	-1	-1
Western Europe	109.5	35.1	32.1	61.6	56.3	26.5	75	43
Russian Federation	1,674.1	130.1	7.8	214.1	12.8	84.0	65	39
Central America & Caribbean	271.8	43.5	16.0	47.5	17.5	4.0	9	8
South America	1,777.6	114.8	6.5	531.9	29.9	417.1	363	78
Oceania & Polynesia	849.7	53.2	6.3	72.9	8.6	19.7	37	27
Eastern Africa	639.5	46.0	7.2	199.0	31.1	153.0	333	77
Middle Africa	657.1	24.8	3.8	184.5	28.1	159.7	645	87
Northern Africa	794.1	44.1	5.6	74.9	9.4	30.7	70	41
Southern Africa	266.4	17.4	6.5	15.7	5.9	–1.7	–10	–11
Western Africa	633.0	65.4	10.3	126.0	19.9	60.6	93	48
Western Asia	433.0	46.1	10.6	29.5	6.8	–16.6	–36	–56
Southeast Asia	444.5	89.6	20.2	75.3	16.9	–14.3	–16	–19
South Asia	671.8	231.6	34.5	167.9	25.0	–63.8	–28	–38
East Asia & Japan	1,149.5	144.1	12.5	127.1	11.1	–17.0	–12	–13
Central Asia	414.4	45.2	10.9	12.3	3.0	–32.9	–73	–268
Developing	8,171.5	909.6	11.1	1,584.5	19.4	674.8	74	43
Developed	5,228.0	595.5	11.4	902.2	17.3	306.6	51	34
World total	13,399.5	1505.2	11.2	2,486.6	18.6	981.5	65	39

[a] *Source:* FAOSTAT, Rome.

Table 5.15. Gross extents of land with rain-fed cultivation potential including marginal areas (VS+S+MS+mS), maximizing technology mix.[a]

Region	Total land (10^6 ha)	Land with cultivation potential (10^6 ha)	Land with cultivation potential (%)	High input level VS[b] (10^6 ha)	High input level S (10^6 ha)	Intermediate input level VS (10^6 ha)	Intermediate input level S (10^6 ha)	Intermediate input level MS (10^6 ha)	Low input level S (10^6 ha)	Low input level MS (10^6 ha)	Low input level mS (10^6 ha)	NS (10^6 ha)
North America	2,138.5	471.9	22.1	87.5	130.7	5.0	34.2	70.6	0.9	37.4	105.6	1,666.6
Eastern Europe	171.0	131.6	77.0	21.9	41.7	1.1	13.5	31.6	0.5	11.7	9.7	39.3
Northern Europe	172.5	48.7	28.2	6.6	21.2	0.4	3.6	10.0	0.0	1.9	5.0	123.8
Southern Europe	131.6	57.8	43.9	6.5	8.8	0.5	8.1	14.7	1.0	7.0	11.3	73.9
Western Europe	109.5	68.1	62.2	17.7	20.3	1.2	10.8	11.7	0.1	2.5	3.9	41.5
Russian Federation	1,674.1	274.2	16.4	26.8	62.8	4.3	32.3	65.6	0.7	33.4	48.3	1,400.0
Central America & Caribbean	271.8	70.3	25.9	17.5	19.7	0.1	5.6	12.2	0.2	3.5	11.5	201.4
South America	1,777.6	771.5	43.4	220.1	297.2	1.4	29.5	108.1	0.3	12.6	102.4	1,006.0
Oceania & Polynesia	849.7	132.3	15.6	28.1	28.8	0.2	8.3	31.6	0.1	4.6	30.5	717.4
Eastern Africa	639.5	286.0	44.7	74.3	80.3	1.3	13.2	61.3	0.2	10.3	45.1	353.5
Middle Africa	657.0	311.4	47.4	103.4	117.3	0.1	4.4	41.1	5	4.1	41.1	345.6
Northern Africa	794.1	103.6	13.1	45.5	25.4	0.6	3.4	15.6	0.4	3.1	9.7	690.5
Southern Africa	266.4	40.5	15.2	2.2	4.1	0.5	5.8	12.3	0.3	3.6	11.7	225.9
Western Africa	633.0	194.0	30.7	60.2	76.2	0.3	8.2	32.9	0	0.8	15.4	439.0
Western Asia	433.0	43.2	10.0	0.8	4.2	0.3	2674	15.0	0.8	7.9	11.4	389.9
Southeast Asia	444.5	116.2	26.1	37.6	50.9	0.4	1.5	11.0	0	0.6	14.2	328.3
South Asia	671.8	214.7	32.0	94.3	71.3	0.4	4.3	22.1	0.1	3.7	18.7	457.2
East Asia & Japan	1,149.5	181.0	15.7	42.9	46.3	0.3	12.5	33.4	0.5	9.0	36.2	968.5
Central Asia	414.4	42.5	10.2	0.5	0.8	0.3	1.3	7.9	0.2	4.5	27.0	371.9
Developing	8,171.5	2,369.1	29.0	697.6	793.5	5.8	91.1	370.5	2.9	63.3	344.3	5,802.4
Developed	5,228.0	1,190.5	22.8	196.9	314.4	12.7	112.0	238.0	3.3	98.8	214.4	4,037.6
World total	13,399.5	3,559.5	26.6	894.4	1,107.9	18.5	203.1	608.5	6.2	162.1	558.7	9,840.0

[a]For the definition of maximizing technology mix, see text at beginning of Section 5.4.
[b]VS = very suitable; S = suitable; MS = moderately suitable; mS = marginally suitable; NS = not suitable.

Table 5.16. Per capita land in use for cultivation and net rain-fed cultivation potential for cereals, population of 1995 and projected population in 2050.

Region	Population[a] 1995	Population[a] 2050	Total land	Land use for cultivation 1994–1996		Rain-fed VS+S+MS net potential land (mixed input)		Rain-fed VS+S net potential land (high input)		Per capita land use 1994–1996	Per capita VS+S+MS land (mixed input) 1995	Per capita VS+S+MS land (mixed input) 2050	Per capita VS+S land (high input) 1995	Per capita VS+S land (high input) 2050
	10^6		(10^6 ha)	10^6 ha	%	10^6 ha	%	10^6 ha	%	(ha/pers.)	ha/pers.		ha/pers.	
North America	296.6	437.5	2,138.5	225.3	10.5	360.7	16.9	214.5	10.0	0.76	1.22	0.82	0.72	0.49
Eastern Europe	162.0	118.5	171.0	81.7	47.8	118.2	69.1	61.7	36.1	0.50	0.73	1.00	0.38	0.52
Northern Europe	93.4	92.6	172.5	21.6	12.5	42.3	24.5	26.8	15.5	0.23	0.45	0.46	0.29	0.29
Southern Europe	143.4	116.8	131.6	45.6	34.7	44.8	34.0	14.6	11.1	0.32	0.31	0.38	0.10	0.12
Western Europe	181.4	170.9	109.5	35.1	32.1	61.4	56.1	36.2	33.0	0.19	0.34	0.36	0.20	0.21
Russian Federation	148.5	104.3	1,674.1	130.1	7.8	223.2	13.3	88.4	5.3	0.88	1.50	2.14	0.60	0.85
Central America & Caribbean	159.0	269.7	271.8	43.5	16.0	57.4	21.1	36.4	13.4	0.27	0.36	0.21	0.23	0.13
South America	317.5	535.5	1,777.6	114.8	6.5	664.3	37.4	513.7	28.9	0.36	2.09	1.24	1.62	0.96
Oceania & Polynesia	28.3	46.9	849.6	53.2	6.3	101.4	11.9	56.7	6.7	1.88	3.58	2.16	2.00	1.21
Eastern Africa	219.5	688.5	639.5	46.0	7.2	237.5	37.1	152.6	23.9	0.21	1.08	0.34	0.70	0.22
Middle Africa	83.3	340.6	657.1	24.8	3.8	268.5	40.9	219.2	33.4	0.30	3.22	0.78	2.63	0.64
Northern Africa	157.8	303.0	794.1	44.1	5.6	92.9	11.7	70.3	8.9	0.28	0.59	0.30	0.45	0.23
Southern Africa	47.3	56.9	266.4	17.4	6.5	28.4	10.6	6.2	2.3	0.37	0.60	0.50	0.13	0.11
Western Africa	209.4	607.9	633.0	65.4	10.3	174.7	27.6	133.3	21.1	0.31	0.83	0.28	0.64	0.21
Western Asia	149.9	408.6	433.0	46.1	10.6	30.7	7.1	4.8	1.1	0.31	0.21	0.07	0.03	0.01
Southeast Asia	481.1	798.9	444.5	89.6	20.2	97.4	21.9	84.6	19.0	0.19	0.20	0.12	0.18	0.10
South Asia	1,312.7	2,456.4	671.8	231.6	34.5	180.0	26.8	151.3	22.5	0.18	0.14	0.07	0.12	0.06
East Asia & Japan	1,420.9	1,664.7	1,149.5	144.1	12.5	132.7	11.5	80.5	7.0	0.10	0.09	0.08	0.06	0.05
Central Asia	70.6	96.8	414.4	45.2	10.9	15.0	3.6	1.2	0.3	0.64	0.21	0.15	0.02	0.01
Developing	4,510.8	8,134.3	8,171.5	909.6	11.1	1,974.4	24.2	1,452.7	17.8	0.20	0.44	0.24	0.32	0.18
Developed	1,171.7	1,180.8	5,228.0	595.5	11.4	957.1	18.3	500.4	9.6	0.51	0.82	0.81	0.43	0.42
World total	5,682.4	9,315.0	13,399.5	1,505.2	11.2	2,931.5	21.9	1,953.1	14.6	0.26	0.52	0.31	0.34	0.21

[a] *Source:* Projected data for 2050 from UN medium variant (United Nations, 2001).

Table 5.17. Per capita land in use for cultivation and net rain-fed cultivation potential for cereals, population of 1995 and projected population in 2050, excluding areas either under forest or areas that are legally protected.[a]

Region	Population[a] 1995	Population[a] 2050	Total land	Land use for cultivation 1994–1996		Rain-fed VS+S+MS net potential land (mixed input)		Rain-fed VS+S net potential land (high input)		Per capita land use 1994–1996	Per capita VS+S+MS land (mixed input) 1995	Per capita VS+S+MS land (mixed input) 2050	Per capita VS+S land (high input) 1995	Per capita VS+S land (high input) 2050
	10^6		(10^6 ha)	10^6 ha	%	10^6 ha	%	10^6 ha	%	(ha/pers.)	ha/pers.		ha/pers.	
North America	296.6	437.5	2,138.5	225.3	10.5	264.7	12.4	160.7	7.5	0.76	0.89	0.60	0.54	0.37
Eastern Europe	162.0	118.5	171.0	81.7	47.8	105.8	61.9	54.9	32.1	0.50	0.65	0.89	0.34	0.46
Northern Europe	93.4	92.6	172.5	21.6	12.5	31.0	18.0	22.1	12.8	0.23	0.33	0.33	0.24	0.24
Southern Europe	143.4	116.8	131.6	45.6	34.7	41.7	31.7	14.0	10.6	0.32	0.29	0.36	0.10	0.12
Western Europe	181.4	170.9	109.5	35.1	32.1	56.3	51.4	34.2	31.3	0.19	0.31	0.33	0.19	0.20
Russian Federation	148.5	104.3	1674.1	130.1	7.8	152.9	9.1	59.3	3.5	0.88	1.03	1.47	0.40	0.57
Central America & Caribbean	159.0	269.7	271.8	43.5	16.0	42.8	15.8	28.3	10.4	0.27	0.27	0.16	0.18	0.10
South America	317.5	535.5	1,777.6	114.8	6.5	435.7	24.5	328.8	18.5	0.36	1.37	0.81	1.04	0.61
Oceania & Polynesia	28.3	46.9	849.6	53.2	6.3	87.7	10.3	49.3	5.8	1.88	3.10	1.87	1.74	1.05
Eastern Africa	219.5	688.5	639.5	46.0	7.2	229.8	35.9	148.3	23.2	0.21	1.05	0.33	0.68	0.21
Middle Africa	83.3	340.6	657.1	24.8	3.8	199.0	30.3	160.9	24.5	0.30	2.39	0.58	1.93	0.47
Northern Africa	157.8	303.0	794.1	44.1	5.6	88.1	11.1	65.9	8.3	0.28	0.56	0.29	0.42	0.22
Southern Africa	47.3	56.9	266.4	17.4	6.5	28.0	10.5	6.2	2.3	0.37	0.59	0.49	0.13	0.11
Western Africa	209.4	607.9	633.0	65.4	10.3	156.6	24.7	119.9	18.9	0.31	0.75	0.25	0.57	0.19
Western Asia	149.9	408.6	433.0	46.1	10.6	30.3	7.0	4.8	1.1	0.31	0.20	0.07	0.03	0.01
Southeast Asia	481.1	798.9	444.5	89.6	20.2	85.5	19.2	74.3	16.7	0.19	0.18	0.10	0.15	0.09
South Asia	1,312.7	2,456.4	671.8	231.6	34.5	175.1	26.1	147.7	22.0	0.18	0.13	0.07	0.11	0.06
East Asia & Japan	1,420.9	1,664.7	1,149.5	144.1	12.5	127.0	11.1	79.1	6.9	0.10	0.09	0.08	0.06	0.05
Central Asia	70.6	96.8	414.4	45.2	10.9	14.8	3.6	1.2	0.3	0.64	0.21	0.15	0.02	0.01
Developing	4,510.8	8,134.3	8,171.5	909.6	11.1	1,607.9	19.7	1,163.3	14.2	0.20	0.36	0.19	0.26	0.14
Developed	1,171.7	1,180.8	5,228.0	595.5	11.4	744.9	14.2	396.7	7.6	0.51	0.64	0.63	0.34	0.34
World total	5,682.4	9,315.0	13,399.5	1,505.2	11.2	2,352.8	17.6	1,560.0	11.6	0.26	0.41	0.25	0.27	0.17

[a] *Sources:* Global Forest Resources Assessment 2000, FAO, Rome, 2001. Protected areas information, UNEP-WCMC, 2001.

With very few exceptions (notably Australia, Russia, and North America), most regions were characterized by a use of arable land per person in the mid-1990s of some 0.1 to 0.4 ha. The world average in 1995 was about 0.25 ha/person for a world population of almost 5.7 billion people. The results suggest a considerable availability of land resources suitable for agricultural uses when considering potentially very suitable, suitable, and moderately suitable land under mixed inputs, even when excluding closed forests and protected areas (*Table 5.17*). However, we do not hesitate to state that such increased use of cultivated land is neither likely – because of improvements in input use and technology leading to higher average per hectare output, and because of competition with other nonagricultural uses – nor desirable, because of obvious implications for biodiversity and the global carbon cycle.

5.5 Where Irrigation Matters

The results from GAEZ have been examined to highlight areas where irrigation can make a significant contribution to land productivity. After processing each land unit of the land resources inventory, individual 5-minute latitude/longitude grid-cells were classified according to the potential impact that the application of irrigation has on suitable extents and production of cereals. The grid-cell results were aggregated according to impact classes by regions and countries, using an algorithm proceeding in six steps (see Box).

By definition, there is no or little contribution from irrigation to the production potential in areas grouped in impact classes 1, 2, and 6. On the other hand, the potential contribution from irrigation is particularly great in impact classes 4 and 5. The impact of irrigation on both suitable extents and cereal production potential were quantified. Results were compiled for different levels of minimum threshold $SH_{\min}$, namely of 1%, 5%, 10%, and 25%. Summaries are available in the form of tables and maps.

The analysis provides interesting insights regarding the potential role of irrigation in the various regions:

- Full exploitation of potential irrigable land increases the global gross extent of suitable land (VS+S+MS) for cereals by 7% to 11%[6] above the land potentially suitable under rain-fed conditions (see *Table 5.18*). Regional results vary substantially, e.g., 5% in South America and 80% in Western Asia. The regions with the largest relative increases are in descending order Central Asia, Western Asia, Southern Africa, Oceania, and Northern Africa (see *Table 5.19*).
- The impact of irrigation is more pronounced on potential production than on potential area. The cereal production potential increases by 32% to 47% (see

Algorithm

For each land unit within each 5-minute latitude/longitude grid-cell in the land resources inventory, the algorithm proceeds in six steps:

Step 1: Determine the crop (or multiple crop combination) that maximizes expected food grain output under rain-fed conditions;
Step 2: Determine the crop (or multiple crop combination) that maximizes expected food grain output under irrigation conditions;
Step 3: Determine the fraction of land in each 5-minute latitude/longitude grid-cell that is assessed as very suitable or suitable under irrigation. Test whether the irrigable share exceeds a specified minimum threshold $SH_{\min}$;
Step 4: Combine rain-fed and irrigated production so as to maximize total output in each grid-cell;
Step 5: Determine the ratio of potential cereal output under rain-fed and/or irrigation conditions to cereal potential under rain-fed conditions only, and
Step 6: Aggregate results by country and region into six irrigation impact classes according to the following scheme:

1. Areas where rain-fed cereal crops can be cultivated but irrigation is impossible or the irrigable share in a grid-cell is below the specified threshold $SH_{\min}$ (due to soil and slope conditions);
2. The irrigable share in a grid-cell exceeds the minimum threshold $SH_{\min}$; irrigation increases potential cereal output of the respective grid-cell by less than 20% above rain-fed levels;
3. As for 2, but irrigation increases grid-cell production potential 20–50%;
4. As for 2, but irrigation increases grid-cell production potential 50–100%;
5. As for 2, but irrigation increases grid-cell production potential $>$ 100%; and
6. No rain-fed production possible and no or too little suitability under irrigation.

Table 5.18. Potential impact of irrigation on global cereal suitability and production.

	Land with suitability for irrigation:		Contribution of irrigation to:	
Irrigation threshold $SH_{\min}$	Share in total suitable land (%)	Share of impact classes 4 + 5 in total irrigable land (%)	Total suitable land (%)	Potential production (%)
1%	40.0	48.2	10.6	46.8
5%	38.5	49.2	10.2	45.0
10%	36.2	50.7	9.5	42.0
25%	28.3	55.1	7.1	32.5

Table 5.19. Potential impact of irrigation on cereal cultivation.[a]

Region	Increase due to irrigation: Suitable land (%)	Increase due to irrigation: Production potential (%)	Percentage of suitable land according to impact of irrigation on cereal productivity: 0–20%	20–50%	$> 50\%$
North America	17	44	53	19	27
Eastern Europe	4	14	82	13	6
Northern Europe	3	9	85	15	0
Southern Europe	9	38	61	18	21
Western Europe	2	10	86	10	4
Russian Federation	14	31	71	12	17
Central America & Caribbean	11	54	49	20	32
South America	5	29	65	18	16
Oceania & Polynesia	45	250	26	6	68
Eastern Africa	7	49	54	20	26
Middle Africa	2	26	64	19	16
Northern Africa	29	112	35	20	46
Southern Africa	53	332	40	6	54
Western Africa	6	39	65	15	20
Western Asia	80	403	30	9	61
Southeast Asia	2	14	72	22	6
South Asia	7	68	34	24	42
East Asia & Japan	12	30	61	9	29
Central Asia	231	733	12	3	85
Developing	8	43	58	18	24
Developed	16	53	61	14	25
World Total	10	45	59	17	24

[a] $SH_{\min}$ is taken as 5%.

Table 5.18). The regions with the largest relative increase are in descending order Central Asia, Western Asia, Southern Africa, Oceania, and Northern Africa (see *Table 5.19*).

- In about 24% of areas suitable for cereals under rain-fed and/or irrigation conditions, the application of supplementary or full irrigation would increase potential output by more than 50% above rain-fed levels. In another 17% of these suitable areas, potential output would benefit from irrigation between 20% and 50% (see *Table 5.19*).
- Overall, application of irrigation has a slightly higher impact in the developed countries than in developing countries, for both increases in extents of arable areas (16% and 8%, respectively) and potential output (53% and 43%, respectively (see *Table 5.19*).

Table 5.20. Value and nutritive weighting factors of cereals used for determining "best" crop.

	Unit value ($/ton)	Calorie content (kcal/100g)	Protein content (g/kg)	Food conversion rate (%)	Food energy weight	Nutritive weight
Wheat	161	334	122	78	261	299
Rice	263	360	67	67	241	259
Maize	142	356	95	92	328	362
Barley	138	337	75	82	276	301
Sorghum	126	343	101	95	326	364
Rye	124	319	110	80	255	290
Millet	125	340	97	95	323	360

The geographical distribution of irrigation impact classes for areas suitable for cereal production is shown in Plate I in this report (Plate 47 on CD-ROM).

5.6 Best Cereal

Another interesting application with the results of AEZ concerns the comparison of agronomic suitability among cereals[7] and selection of the cereal type with the highest overall suitability for individual land units of each 5-minute grid-cell. It is quite possible, for instance, that a certain land unit is very suitable for pearl millet and only moderately suitable for grain maize. Pearl millet would be the crop that is best agronomically suited to that particular environment, while the grain yield of the moderately suitable maize could exceed the yield of the millet. Therefore, a comparison is also presented in terms of food production, using nutritive values and conversion rates as weights. A third option is to compare yields and production in value terms. Weighting factors for crop selection by output value and nutritive content are shown in *Table 5.20*.

Plate 48 (CD-ROM) presents a map showing the "best" cereal in terms of agronomic suitability, Plate 49 (CD-ROM) shows a map of the "best" cereal in terms of food energy, and Plate 50 (CD-ROM) displays the "best" cereal according to output value, using average 1994–1998 world export unit values for comparison (see *Table 5.21* for regional results and Spreadsheet 10 (CD-ROM) for country results).

When selecting among cereal crops on the basis of expected value of output, then wheat (and barley), rice, and grain maize each dominate in around 30% of the total suitable rain-fed areas. The remaining cereals (rye, sorghum, foxtail millet and pearl millet) together would be chosen in merely 6% of the area. In terms of production, grain maize provides the largest share of some 40%, followed by wheat and rice, each contributing 28% (see *Table 5.21*).

Table 5.21. Distribution of "best" rain-fed crops when using as selection criterion the crop output value per land unit by region.

Region	Gross suitable area (VS+S+MS) (10^6 ha)	Share in suitable area (%) Wheat, barley	Rice	Maize	Other cereals	Potential usable production (10^6 tons)	Share in potential production (%) Wheat, barley	Rice	Maize	Other cereals
North America	280.3	81.6	0.5	17.5	0.4	847.8	79.0	0.3	20.5	0.2
Eastern Europe	89.0	100.0	0.0	0.0	0.0	296.1	100.0	0.0	0.0	0.0
Northern Europe	35.9	99.7	0.0	0.0	0.3	110.6	99.9	0.0	0.0	0.1
Southern Europe	21.1	99.3	0.4	0.1	0.2	68.1	99.5	0.3	0.1	0.1
Western Europe	47.5	99.8	0.0	0.2	0.0	171.5	99.9	0.0	0.1	0.0
Russian Federation	168.9	99.7	0.0	0.1	0.2	378.4	99.7	0.0	0.2	0.1
Central America & Caribbean	39.2	7.8	59.7	27.2	5.2	116.1	5.6	58.0	33.2	3.1
South America	527.0	7.7	64.8	24.7	2.7	1,505.3	6.2	62.1	29.6	2.1
Oceania & Polynesia	72.3	34.6	8.9	40.2	16.3	191.2	27.6	8.7	51.4	12.2
Eastern Africa	189.4	4.4	13.0	74.2	8.4	630.9	2.3	11.2	82.2	4.3
Middle Africa	200.2	0.3	58.2	37.7	3.8	612.2	0.1	51.9	45.7	2.2
Northern Africa	76.5	5.6	8.6	70.4	15.4	269.9	2.8	7.1	82.4	7.7
Southern Africa	8.7	9.8	0.0	55.7	34.5	19.1	6.8	0.0	69.1	24.1
Western Africa	143.8	0.0	26.4	56.0	17.7	453.3	0.0	22.7	67.4	9.9
Western Asia	10.5	100.0	0.0	0.0	0.0	24.2	100.0	0.0	0.0	0.0
Southeast Asia	87.2	2.5	85.4	11.8	0.3	244.4	1.0	86.2	12.5	0.2
South Asia	184.8	0.8	15.9	68.3	14.9	613.3	0.5	14.5	73.8	11.3
East Asia & Japan	119.6	13.6	21.9	48.3	16.2	321.4	13.8	22.6	55.7	8.0
Central Asia	6.0	98.9	1.1	0.0	0.0	10.7	98.7	1.3	0.0	0.0
Developing	1,591.3	5.6	42.9	43.4	8.0	4,811.9	4.0	39.3	51.7	5.0
Developed	716.7	86.4	0.8	10.9	1.9	2,072.7	84.9	0.7	13.1	1.2
World total	2,308.0	30.7	29.8	33.3	6.1	6,884.7	28.4	27.7	40.1	3.9

Table 5.22. Distribution of "best" rain-fed crops when using nutrition as weight in crop selection by region.

Region	Gross suitable area (VS+S+MS) (10^6 ha)	Share in suitable area (%)				Potential usable production (10^6 tons)	Share in potential production (%)			
		Wheat, barley	Rice	Maize	Other cereals		Wheat, barley	Rice	Maize	Other cereals
North America	278.2	66.1	0.3	31.5	2.1	839.3	64.1	0.2	34.5	1.2
Eastern Europe	89.0	99.5	0.0	0.5	0.0	296.0	99.4	0.0	0.6	0.0
Northern Europe	36.0	99.2	0.0	0.0	0.8	110.8	99.7	0.0	0.0	0.3
Southern Europe	21.2	89.3	0.0	10.5	0.2	68.0	86.8	0.0	13.2	0.1
Western Europe	47.6	99.6	0.0	0.3	0.1	171.7	99.7	0.0	0.3	0.1
Russian Federation	171.1	97.8	0.0	1.8	0.3	380.0	97.9	0.0	1.9	0.2
Central America & Caribbean	36.0	6.1	42.7	44.6	6.7	111.6	4.0	41.4	50.5	4.1
South America	515.2	4.2	58.0	32.6	5.2	1,493.1	3.0	55.4	37.3	4.2
Oceania & Polynesia	71.5	31.5	6.4	37.5	24.6	192.4	24.6	6.4	48.5	20.5
Eastern Africa	188.5	3.2	3.7	79.6	13.6	650.7	1.6	3.2	86.7	8.5
Middle Africa	195.8	0.2	47.0	46.7	6.1	618.2	0.1	40.4	55.3	4.2
Northern Africa	77.1	5.7	1.4	73.9	19.0	277.2	2.8	1.2	85.6	10.4
Southern Africa	8.8	6.9	0.0	43.7	49.4	19.5	4.7	0.0	55.1	40.3
Western Africa	140.2	0.0	15.2	62.8	22.0	456.0	0.0	13.3	73.4	13.4
Western Asia	10.5	100.0	0.0	0.0	0.0	24.1	100.0	0.0	0.0	0.0
Southeast Asia	81.9	2.4	55.1	42.0	0.6	240.3	0.9	53.0	45.7	0.4
South Asia	185.1	0.7	5.2	71.9	22.2	638.5	0.4	5.0	77.6	17.0
East Asia & Japan	118.8	4.5	1.2	71.8	22.4	338.5	4.5	1.2	81.9	12.4
Central Asia	5.9	94.6	0.8	4.6	0.0	10.6	90.6	1.0	8.4	0.0
Developing	1,561.9	3.7	31.7	52.7	11.8	4,866.7	2.4	28.4	61.0	8.2
Developed	716.5	79.1	0.2	17.4	3.4	2,069.7	77.3	0.1	20.1	2.5
World total	2,278.4	27.4	21.8	41.6	9.2	6,936.4	24.7	20.0	48.8	6.5

The picture changes a bit when nutritive factors are used for weighting crop production prior to selecting a "best" crop. In this case, grain maize takes a somewhat larger share of 42% in total suitable area while the share of rice is decreased in comparison to a selection based on price rather than nutrition (from 30% to 22%). Results for wheat/barley remain nearly the same. These differences in area distribution are also reflected in the resulting output pattern. Grain maize accounts for 49% of total output when selecting among cereals according to nutritive content, rice contributes 20%, wheat and barley together account for 25%, and close to 7% go to sorghum, rye, and millet (see *Table 5.22* for regional results and Spreadsheet 10 [CD-ROM] for country results).

5.7 Multiple Cropping Land Productivity

A multiple cropping zones classification (see Section 4.7) is used to determine feasible crop combinations (sequential cropping patterns) in each 5-minute latitude/longitude grid-cell of the land resources inventory.

In our calculations, crops qualify only when they are individually suitable and can be combined within the available growing period (LGP for rain-fed conditions, or LGP$_{t=5}$ for irrigated conditions). Dryland crops are allowed to overlap partly (relay cropping with less than 30% overlap). Zones where relay cropping is required for double or triple cropping are referred to as "limited" double (C) or "limited" triple (F) cropping zones. It is assumed that relay cropping is not applicable to wetland-wetland or wetland-dryland crop combinations. An example of land production potential of cereals by multiple cropping zones is presented in *Table 5.23*. This table is complemented by Plate J in this report (Plate 53 on CD-ROM), which presents the global distribution of the land production potential of cereals, under rain-fed conditions.

The selection of an optimal cereal crop combination can be described as the task of matching the requirements of the suitable crop types with the characteristics of a particular grid-cell in such a way that a maximum grain production can be obtained. The AEZ algorithm uses a scheme of eight generic crop groups, based on a distinction of crop growth cycle length and thermal requirements, to determine feasible (within-year) sequential multi-cropping patterns. Each crop LUT belongs to one of these eight groups.

In the case of a single-cropping zone, the selection of the most productive cereal is easy. The algorithm compares the grid-cell characteristics with the requirements of each cereal LUT. Among those grains that fit, the algorithm selects the one producing the highest potential production. In the case of multi-cropping, the selection is more complicated. The algorithm cannot practically test all possible combinations of the 83 available crop types – this would prohibitively increase the

Table 5.23. Gross area and production potential for cereals at high input level, by multiple cropping zones by region.

		Share of total suitable area and multiple cropping production potential for cereals at high input level																		
	Total land area	Total VS+S+MS area	Land with cultivation potential shares								Total VS+S+MS production	Multiple cropping production shares							
Region	(10^6 ha)	(10^6 ha)	Zone A (%)	Zone B (%)	Zone C (%)	Zone D (%)	Zone E (%)	Zone F (%)	Zone G (%)	Zone H (%)	(10^6 tons)	Zone A (%)	Zone B (%)	Zone C (%)	Zone D (%)	Zone E (%)	Zone F (%)	Zone G (%)	Zone H (%)
North America	2,138.5	286.7	0.0	35.6	17.6	14.3	9.4	6.4	14.5	2.1	1,259.9	0.0	21.6	15.9	14.4	11.3	9.0	23.6	4.2
Eastern Europe	171.0	92.9	0.0	95.1	4.9	0.0	0.0	0.0	0.0	0.0	355.4	0.0	95.0	5.0	0.0	0.0	0.0	0.0	0.0
Northern Europe	172.5	38.7	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	135.2	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0
Southern Europe	131.6	21.4	0.0	56.9	35.1	8.0	0.0	0.0	0.0	0.0	80.5	0.0	48.8	42.1	9.1	0.0	0.0	0.0	0.0
Western Europe	109.5	47.7	0.0	97.2	2.6	0.2	0.0	0.0	0.0	0.0	202.4	0.0	97.2	2.6	0.2	0.0	0.0	0.0	0.0
Russian Federation	1,674.1	184.6	0.0	99.1	0.9	0.0	0.0	0.0	0.0	0.0	471.4	0.0	98.5	1.5	0.0	0.0	0.0	0.0	0.0
Central America & Caribbean	271.8	45.5	0.0	22.7	9.0	41.7	0.0	19.6	0.0	7.0	199.0	0.0	16.5	11.6	51.9	0.0	12.6	0.0	7.5
South America	1,777.6	663.2	0.0	8.5	5.8	43.7	2.0	19.5	5.6	14.9	2,942.2	0.0	5.7	6.2	47.0	2.3	12.4	8.1	18.3
Oceania & Polynesia	849.7	78.7	0.0	74.5	5.7	5.6	3.8	3.0	2.4	5.0	264.3	0.0	65.3	6.9	8.0	4.3	4.3	4.2	6.9
Eastern Africa	639.5	201.1	0.0	56.7	25.1	15.7	0.0	1.1	0.0	1.4	880.3	0.0	51.0	29.6	17.7	0.0	0.5	0.0	1.2
Middle Africa	657.1	266.9	0.0	20.5	9.3	35.1	0.0	19.7	0.0	15.4	1,080.1	0.0	21.4	12.3	37.6	0.0	11.4	0.0	17.2
Northern Africa	794.1	81.0	0.0	60.8	24.7	14.5	0.0	0.0	0.0	0.0	374.7	0.0	50.4	33.2	16.4	0.0	0.0	0.0	0.0
Southern Africa	266.4	9.7	0.0	77.2	19.2	1.4	1.2	0.5	0.5	0.0	24.9	0.0	68.5	23.2	2.4	2.7	1.5	1.7	0.0
Western Africa	633.0	169.8	0.0	47.4	14.1	31.7	0.0	6.7	0.0	0.1	697.1	0.0	42.6	18.9	34.9	0.0	3.5	0.0	0.2
Western Asia	433.0	10.9	0.0	98.5	1.5	0.0	0.0	0.0	0.0	0.0	29.2	0.0	97.8	2.2	0.0	0.0	0.0	0.0	0.0
Southeast Asia	444.5	112.2	0.0	0.4	2.0	60.7	2.4	6.6	0.0	27.7	547.6	0.0	0.4	2.1	64.4	2.7	3.8	0.0	26.6
South Asia	671.8	191.4	0.0	72.2	13.8	9.7	3.1	0.5	0.4	0.3	828.1	0.0	64.7	16.9	12.5	4.6	0.4	0.5	0.3
East Asia & Japan	1,149.5	121.1	0.0	38.0	7.9	6.2	20.8	16.7	8.5	1.9	531.6	0.0	18.9	6.2	6.1	27.5	26.3	12.3	2.7
Central Asia	414.4	6.2	0.0	92.8	2.5	3.8	0.9	0.0	0.0	0.0	13.2	0.0	86.6	5.8	6.1	1.5	0.0	0.0	0.0
Developing	8,171.5	1,879.0	0.0	30.4	10.7	31.6	2.4	12.5	2.6	9.8	8,146.7	0.0	25.2	12.8	34.9	3.2	8.7	3.8	11.4
Developed	5,228.0	750.5	0.0	70.9	9.4	6.3	4.2	2.6	5.8	0.8	2,770.2	0.0	58.8	10.4	7.6	5.8	4.4	11.1	1.9
World total	13,399.5	2,629.5	0.0	41.9	10.3	24.4	2.9	9.7	3.5	7.2	10,916.9	0.0	33.7	12.2	28.0	3.9	7.6	5.6	9.0

A: Zone of no cropping (on average, too cold or too dry for rain-fed crops). B: Zone of single cropping. C: Zone of limited double cropping (relay cropping; single wetland rice may be possible). D: Zone of double cropping (sequential cropping; wetland rice not possible). E: Zone of double cropping (sequential cropping; wetland rice crop possible). F: Zone of limited triple cropping (partly relay cropping; no third crop possible in case of two wetland rice crops). G: Zone of triple cropping (sequential cropping of three short-cycle crops; two wetland rice crops possible). H: Zone of triple rice cropping (sequential cropping of three wetland rice crops possible).

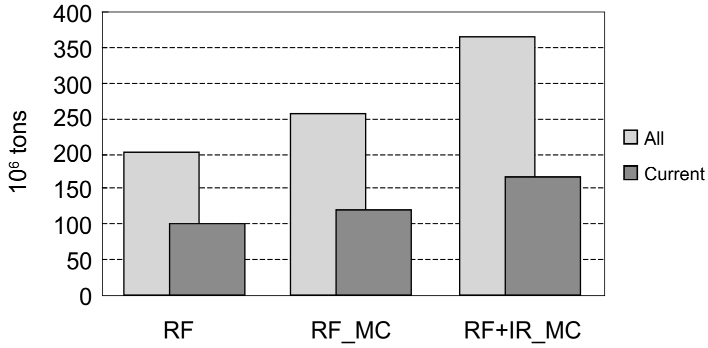

Figure 5.1. Comparison of single rain-fed (RF), multiple rain-fed (RF_MC), and multiple rain-fed and irrigated cereal cropping outputs (RF+IR_MC) for currently cultivated land and all land with cultivation potential.

time needed for the calculations. Instead, only those crops that have the highest yield in each of the eight generic groups are tested as a second or third grain. The rules for constructing cropping patterns have been designed to make sure that the algorithm uses typical crop sequences in cultivation cycles. For instance, in the typical double-cropping areas around Shanghai, the algorithm would select a long-cycle rice or maize crop as the most productive summer crop, and winter wheat or barley (depending on which is more productive) as the winter crop, provided the combination of both grains fits within the LGP of the particular grid-cell. In a triple-cropping zone, either three short-cycle crops or two long-cycle crops are permitted. Regional results are provided in Spreadsheet 11 (CD-ROM). It presents gross area and production potential for cereals at the high input level, by multiple cropping zones and country. Plates 51–54 (CD-ROM) present world maps with expected grid-cell output per hectare for, respectively, (1) single cropping of rain-fed cereals, (2) single cropping of rain-fed and/or irrigated cereals, (3) multiple cropping of rain-fed cereals, and (4) multiple cropping of rain-fed and/or irrigated cereals.

The results in *Table 5.23* are shown as percentage distributions over eight multiple cropping zones, both for suitable land (VS+S+MS) and attainable production from these areas. According to our estimation from an example calculation for cereals, 42% of the land globally suitable for rain-fed cereals falls in zone B (i.e., single cropping), providing 34% of the cereal production potential. Some 38% of the suitable area could produce two crops per year (zones C, D, E), contributing 44% of the global cereal production potential. The remaining 20% of suitable areas could support three crops per annum (zones F, G, H) and produce about 22% of the global cereal production potential.

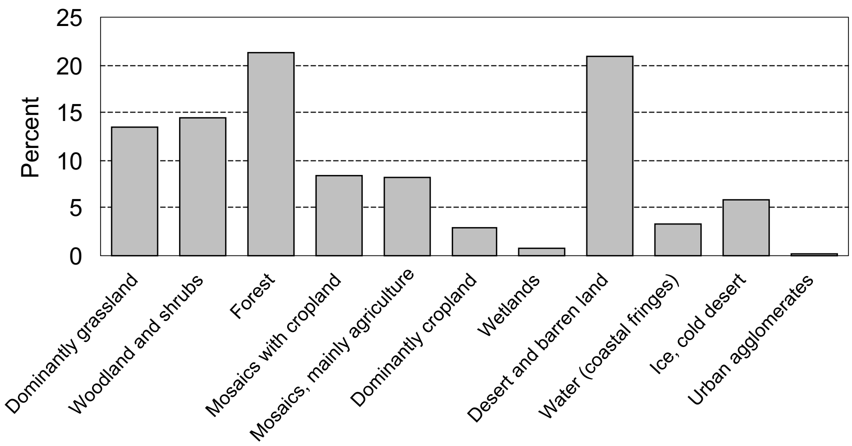

Figure 5.2. World aggregated land cover classes (%).

Figure 5.1 compares at the global level, relative outputs for rain-fed single cropping, rain-fed multiple cropping, and rain-fed and/or irrigated multiple cropping of cereals for land currently under cultivation and all land with cultivation potential. Results show increases of outputs of 21% and 66%, respectively, on currently cultivated land and 25% and 80% on all land with cultivation potential.

5.8 Current Land Cover

Currently, some 1.5 billion ha of land are used for agriculture (average over years 1994–1996 according to FAOSTAT). Meaningful comparison of potentially arable land with presently cultivated land requires that, within the potential arable land, we account for nonagricultural land uses. It is necessary to exclude land needed for infrastructure and human settlement, and to separately account for land set aside for, e.g., forest ecosystems in natural reserves.

In the GAEZ assessment we have used an aggregate ecosystems data set derived from a Global Land Cover Characteristics (GLCC) Database[8] at 30 arc-seconds latitude/longitude (EROS Data Center, 2000). The GLCC database provides interpretations of 1-km advanced very-high-resolution radiometer (AVHRR) data (obtained during April 1992 through March 1993) according to various Legends. We applied the Olson Global Ecosystem classification (Olson, 1994). This classification distinguishes about 100 ecosystem classes (not all classes are present in the data set), which were aggregated into 11 broad ecosystem classes (see Plate 55 on CD-ROM) for use with GAEZ results. The distribution of these aggregate land-cover classes, worldwide and by region, is presented in *Figure 5.2* and *Table 5.24*.

Table 5.24. Distribution of aggregate land cover classes.

	Aggregate land cover classes (%)[a]										
Region	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)	(xi)
North America	6.3	11.1	26.3	7.6	4.0	2.6	1.0	8.5	6.8	25.2	0.4
Eastern Europe	0.5	2.1	9.9	32.2	51.6	0.1	0.0	0.0	2.1	0.0	1.4
Northern Europe	1.5	10.8	41.3	12.6	14.4	0.1	0.7	0.4	11.2	6.2	0.8
Southern Europe	0.6	14.1	19.8	21.8	35.6	0.6	0.0	2.9	4.0	0.3	0.3
Western Europe	0.6	6.2	13.5	6.0	68.8	0.2	0.1	0.2	2.5	0.7	1.3
Russian Federation	4.0	24.6	38.3	5.8	8.7	0.3	3.4	0.4	3.6	10.6	0.2
Central America & Caribbean	13.8	15.3	29.5	6.7	13.8	0.7	0.6	16.0	3.4	0.0	0.1
South America	13.3	15.4	39.2	14.8	3.4	2.9	0.3	5.6	2.9	2.0	0.1
Oceania & Polynesia	26.2	31.6	8.4	0.4	6.2	0.1	0.0	24.4	2.5	0.0	0.1
Eastern Africa	25.8	23.5	5.1	10.5	15.4	0.0	0.0	15.9	3.7	0.0	0.0
Middle Africa	15.5	31.7	29.3	4.8	5.2	0.0	0.1	11.6	1.9	0.0	0.0
Northern Africa	9.7	8.3	0.6	1.4	0.9	0.2	0.3	78.1	0.4	0.0	0.0
Southern Africa	38.4	0.6	1.6	17.8	7.2	0.0	0.1	33.9	0.3	0.0	0.1
Western Africa	25.4	16.3	2.1	6.1	2.3	0.1	0.5	46.0	1.2	0.0	0.0
Western Asia	5.2	0.5	1.8	6.5	5.8	0.3	0.0	78.5	1.2	0.1	0.1
Southeast Asia	3.8	3.0	51.3	10.7	9.1	17.6	0.0	0.1	4.0	0.0	0.2
South Asia	7.3	4.5	5.9	8.1	21.1	12.0	0.1	37.8	1.5	1.5	0.1
East Asia & Japan	24.4	7.0	11.5	8.2	6.6	9.6	0.1	29.9	1.9	0.8	0.1
Central Asia	33.2	1.7	2.2	14.3	9.0	2.1	0.0	32.1	3.7	1.4	0.2
Developing	17.1	11.9	17.8	9.3	7.2	4.1	0.2	29.3	2.2	0.7	0.1
Developed	8.1	18.5	26.6	7.1	9.9	1.3	1.6	7.7	4.9	13.9	0.4
World total	13.6	14.5	21.2	8.5	8.3	3.0	0.7	20.9	3.3	5.9	0.2

[a](i) Grassland; (ii) Woodland; (iii) Forest; (iv) Mosaics including cropland; (v) Mosaics, mainly agriculture; (vi) Dominantly cropland; (vii) Wetland; (viii) Desert and barren land; (ix) Water (coastal fringes); (x) Ice, cold desert; (xi) Urban.

As an example of combining AEZ results with spatial land-cover information, the extent of land with cultivation potential presently under forest ecosystems was estimated by overlaying the current land cover according to the GLCC database onto land with rain-fed cultivation potential. Our estimation suggests (see *Table 5.25*) that close to 19% of the land with cultivation potential (VS+S+MS) is under forest ecosystems (i.e., 464 million ha out of a total with cultivation potential of 2,430 million ha). A similar share, 17% (i.e., 237 million ha out of 1,380 million ha), holds for very suitable and suitable lands. On a regional scale, the largest shares of land with crop production potential currently under forest are found in South and North America, where more than one third of the potentially cultivable land determined by AEZ is classified as dominantly forest ecosystems according to GLCC. Considerable potentials with forest land cover were also assessed in the sub-humid and humid zones of Central America and Middle Africa. Our results indicate that relatively more land with cultivation potential for major cereals is covered by forest ecosystems in developed countries (about 23%) than in developing countries (about 17%).

Table 5.25, presenting regional and global extents of land with cereal crop cultivation potential under GLCC forest ecosystems, shows rather wide variations among regions. In the Russian Federation, for example, only 9% of the land with forest ecosystems is adjudged to have cultivation potential for one or more of the three major cereals, while in South America this share is as high as 27%. Only 3.5% of forest ecosystems in Russia is considered to be very suitable or suitable (VS+S) for at least one of the three cereal crops; in South America the respective share is 15%.

Spreadsheet 12 (CD-ROM) presents, at the country level, the land potential for rain-fed cultivation of major cereals under forest ecosystems, for all land excluding forest areas, protected areas, and land required for habitation and infrastructure. Plates 56 and 57 (both on CD-ROM) present suitability maps for rain-fed crops for all areas, excluding forest ecosystems and areas classified as being under forest ecosystems.

5.9 Climate Sensitivity

Our experiments with various climate sensitivity scenarios and preliminary results with GCM-based climate scenarios underpin the appropriateness of the AEZ methods for climate change impact assessments. It confirms findings of earlier work with AEZ applications in case studies of Kenya (Fischer and van Velthuizen, 1996) and Nigeria (Voortman *et al.*, 1999), demonstrating that AEZ is very flexible in capturing all three types of impacts: (1) those on yields, (2) those on extents suitable for crop cultivation, and (3) those on changes in the number of crops per year (sequential multi-cropping). AEZ calculation procedures account for a wide range of rational adaptations, thus simulating impacts upon responsive "smart" farmers. Recently, several experiments with GCM-derived climate change scenarios were completed. Also, in order to demonstrate possible effects of climate change on potential distribution patterns of some key crops, a limited set of temperature and rainfall sensitivity scenarios were applied as follows:

- A 1°C, 2°C, and 3°C temperature increase, respectively, uniformly in each month for both minimum and maximum temperatures, and
- Uniformly distributed combined increases of temperature and precipitation of respectively 1°C increase and +5% monthly precipitation, 2°C increase and +5% monthly precipitation, 2°C increase and +10% annual precipitation, and 3°C increase and +10% annual precipitation distributed proportionally over the 12 months.

Table 5.25. Land under forest ecosystems with potential for rain-fed cultivation of major cereals.[a]

Region	Total of forest ecosystems (10^6 ha)	VS+S for wheat, rice, maize (high input)				VS+S+MS for wheat, rice, maize (mixed inputs)			
			Under forest ecosystems				Under forest ecosystems		
		Total (10^6 ha)	Extent (10^6 ha)	% of forest	% of suitable	Total (10^6 ha)	Extent (10^6 ha)	% of forest	% of suitable
North America	562.1	192.9	64.9	11.6	33.7	342.0	114.8	20.4	33.6
Eastern Europe	17.0	57.8	0.9	5.3	1.6	110.9	3.9	23.2	3.6
Northern Europe	63.6	24.0	2.7	4.2	11.2	38.2	8.2	12.9	21.4
Southern Europe	23.9	14.0	0.8	3.4	5.9	43.6	3.5	14.4	7.9
Western Europe	14.3	35.4	0.5	3.4	1.4	58.9	2.1	14.4	3.5
Russian Federation	641.7	74.2	22.2	3.5	29.9	211.5	57.5	9.0	27.2
Central America & Caribbean	70.2	26.2	5.0	7.1	19.0	46.4	10.0	14.3	21.6
South America	680.5	314.0	103.8	15.2	33.0	528.3	186.6	27.4	35.3
Oceania & Polynesia	71.7	35.8	4.5	6.2	12.5	73.1	11.1	15.5	15.2
Eastern Africa	32.8	118.8	2.4	7.2	2.0	196.2	5.4	16.4	2.7
Middle Africa	190.2	112.2	17.0	9.0	15.2	183.4	33.8	17.8	18.4
Northern Africa	4.9	52.7	0.4	7.7	0.7	74.0	0.5	10.8	0.7
Southern Africa	4.2	2.7	0.0	0.7	1.1	15.6	0.5	12.1	3.2
Western Africa	13.5	82.1	1.0	7.6	1.3	123.3	2.1	15.8	1.7
Western Asia	7.6	4.0	0.1	1.0	1.9	28.6	1.0	13.1	3.5
Southeast Asia	207.4	54.0	6.2	3.0	11.5	71.8	10.5	5.1	14.7
South Asia	39.6	116.7	2.1	5.3	1.8	153.9	3.4	8.6	2.2
East Asia & Japan	132.4	62.7	2.3	1.7	3.7	117.3	8.0	6.1	6.8
Central Asia	8.7	1.1	0.2	2.1	16.6	11.9	0.7	8.3	6.0
Developing	1,404.8	944.6	140.1	10.0	14.8	1,544.3	261.0	18.6	16.9
Developed	1,381.4	436.7	96.8	7.0	22.2	884.6	202.8	14.7	22.9
World total	2,786.1	1,381.3	236.9	8.5	17.2	2,428.9	463.8	16.6	19.1

[a] In some countries the extents of forest ecosystems derived from the GLCC exceed the area of forest and woodland published by FAO. In such cases, the estimates of suitable areas under forest ecosystems were adjusted proportionally. Suitable extents are also adjusted for housing and infrastructure land requirements using a spatially explicit gridded global 1995 population distribution database (CIESIN, 2000).

Table 5.26. Impact of temperature and precipitation sensitivity experiments on crop suitability, expressed as VS+S+MS extents for rain-fed wheat cultivation (% change relative to current climate).

	Temperature increase			Temperature increase, and precipitation change			
Region	+1°C	+2°C	+3°C	+1°C, +5%	+2°C, +5%	+2°C, +10%	+3°C, +10%
North America	10.9	14.6	18.1	14.6	18.8	21.3	25.4
Eastern Europe	4.1	0.1	–5.5	8.0	3.4	7.5	2.9
Northern Europe	10.7	10.8	11.4	11.8	11.9	11.1	12.3
Southern Europe	5.7	8.5	9.4	9.6	12.3	16.4	17.2
Western Europe	0.2	–3.1	–5.6	0.1	–2.7	–3.2	–7.1
Russian Federation	21.4	31.1	39.2	25.5	36.1	40.5	48.6
Central America & Caribbean	–9.4	–39.4	–65.3	–9.1	–36.8	–29.7	–60.7
South America	–13.2	–24.3	–34.0	–14.4	–24.1	–23.8	–32.2
Oceania & Polynesia	–4.5	–5.9	–8.8	–1.1	–0.4	2.1	–2.3
Eastern Africa	–44.7	–63.7	–78.4	–46.1	–65.1	–66.8	–80.6
Middle Africa	–50.3	–76.0	–92.0	–53.3	–76.4	–77.2	–91.7
Northern Africa	4.3	5.7	7.6	23.5	24.2	43.6	46.7
Southern Africa	–24.5	–33.1	–51.7	–8.7	–16.0	–2.3	–29.9
Western Africa	–100.0	–100.0	–100.0	–100.0	–100.0	–100.0	–100.0
Western Asia	28.7	51.6	65.3	47.7	66.3	83.6	106.8
Southeast Asia	–11.8	–23.0	–51.6	–18.0	–31.2	–39.7	–59.6
South Asia	–8.1	–28.0	–44.9	–7.3	–25.8	–21.0	–33.3
East Asia & Japan	13.5	4.4	–2.2	13.9	5.8	6.8	–1.9
Central Asia	9.5	7.4	–1.7	29.3	10.7	46.8	41.6
Developing	–12.5	–24.0	–34.4	–10.8	–22.0	–19.0	–28.5
Developed	10.7	13.8	16.2	14.0	17.7	20.5	23.0
World total	3.9	2.8	1.4	6.8	6.0	8.9	7.9

Plate 58 (CD-ROM) shows where and how much length of growing periods are affected by an assumed temperature increase of 2°C.

Considerable shifts occur in the potential wheat distribution even when modest changes of temperature or precipitation are applied. *Table 5.26* presents changes in extents of land very suitable, suitable, and moderately suitable for rain-fed wheat, simulated for the selected temperature and rainfall sensitivity scenarios. *Table 5.27* extends the analysis to the three key cereal crops, i.e., wheat, rice, and grain maize.

Plates 59–62 (CD-ROM) present maps of the potential distribution of rain-fed wheat under current climate, +1°C annual temperature, +2°C combined with +5% annual precipitation, and +3°C combined with +10% annual precipitation, respectively. Plates 63–66 (CD-ROM) present the potential distribution of rain-fed grain maize.

Table 5.27. Impact of temperature and precipitation sensitivity experiments on crop suitability, expressed as VS+S+MS extents for rain-fed wheat, rice, or grain maize cultivation (% change relative to current climate).

	Temperature increase			Temperature increase and precipitation change			
Region	+1°C	+2°C	+3°C	+1°C, +5%	+2°C, +5%	+2°C, +10%	+3°C, +10%
North America	12.0	16.1	20.3	16.1	20.9	23.8	28.4
Eastern Europe	5.7	6.0	0.6	9.6	9.3	13.0	10.3
Northern Europe	10.7	10.8	11.5	11.8	11.9	11.1	12.6
Southern Europe	6.3	10.2	12.1	10.6	14.0	18.6	21.3
Western Europe	0.4	–1.6	–2.9	1.1	–1.0	–1.3	–4.3
Russian Federation	21.6	31.5	40.3	25.8	36.6	41.0	49.7
Central America & Caribbean	–0.5	–3.9	–8.5	–3.7	–6.4	–9.2	–13.4
South America	–4.4	–11.4	–19.8	–6.9	–12.9	–13.9	–22.7
Oceania & Polynesia	–4.1	–4.7	–9.3	0.7	–0.2	3.6	–0.2
Eastern Africa	–4.1	–8.2	–12.3	–5.8	–9.2	–10.9	–14.8
Middle Africa	–2.5	–7.0	–11.2	–7.0	–11.0	–13.7	–17.9
Northern Africa	–1.2	–3.0	–5.2	3.3	1.4	6.1	4.7
Southern Africa	–17.3	–21.5	–30.9	7.9	–4.1	16.9	3.6
Western Africa	–2.2	–8.4	–13.5	–3.4	–7.9	–8.0	–13.4
Western Asia	28.9	51.7	65.2	47.6	66.4	83.4	106.5
Southeast Asia	–2.7	–4.5	–11.7	–6.5	–9.2	–14.0	–21.2
South Asia	–2.6	–6.8	–13.6	–0.8	–5.3	–3.0	–8.7
East Asia & Japan	15.6	16.5	15.9	14.2	15.7	15.2	16.6
Central Asia	13.0	13.9	6.6	31.5	17.3	54.3	51.1
Developing	–1.3	–5.5	–11.1	–2.1	–6.0	–5.9	–11.1
Developed	11.1	15.0	17.7	14.8	19.1	22.2	25.3
World total	3.9	3.1	1.1	5.0	4.6	5.9	4.3

The application of the various temperature and rainfall sensitivity scenarios revealed a modest increase of cultivable rain-fed land (at a global scale) for temperature increases up to 2°C. If temperature increases further but precipitation patterns persist and amounts remain at current levels, the extent of cultivable rain-fed land starts to decrease. When both temperature and precipitation amounts increase, the extent of cultivable rain-fed land increases steadily. For example, a temperature increase of 3°C paired with a precipitation increase of 10% would lead globally to about 4% more cultivable rain-fed land. In the developed countries, this increase is even markedly higher; it exceeds 25%. In contrast, the developing countries would experience a decrease of 11%.

Spreadsheet 13 (CD-ROM) presents at the country level the impacts of temperature and rainfall sensitivity tests on crop suitability, expressed as VS+S+MS extents for rain-fed wheat, rice, or grain maize cultivation (% change relative to current climate).

5.10 Impacts of Climate Change on Cereal Production

The AEZ climate impact assessment is based on the projections of several GCMs, including the ECHAM4 model of the Max-Planck Institute of Meteorology, the HADCM2 model of the Hadley Centre for Climate Prediction and Research, and the CGCM1 model of the Canadian Centre for Climate Modelling and Analysis. A detailed report of the simulation results, including an assessment of the IPCC 2000 emission scenarios (Nakićenović and Swart, 2000) and a comparative AEZ analysis of climate change consequences for food production, is in preparation.

This section illustrates the results of changes in rain-fed cereal production based mainly on the climate change projections of the ECHAM4 model. For this analysis we have assumed a high level of inputs and management. The assessment was carried out for areas classified as being in cultivation in 1992–1993, according to interpretations of remotely sensed AHVRR data, as well as for all land with production potential for rain-fed cereals regardless of current use. Thus the study assesses impacts on current agricultural land and also estimates where major shifts in land productivity might occur. Note that the calculations fully account for optimal adaptations of crop calendars, switching of crop types, as well as changes in potential multi-cropping. This study also incorporates yield increases resulting from higher carbon dioxide concentrations in the atmosphere through so-called CO_2 fertilization.

Taking climate change projections of ECHAM4 for the 2080s (average for 2070–2099), the rain-fed potential cereal production, assuming one crop per year with a high level of inputs on land currently under cultivation, shows a net decrease of some 3.5% at the global level. The results in terms of percentage losses and gains for individual countries are shown in Plate K in this report.

When multiple cropping and irrigation are also taken into account, agricultural systems are better able to adapt to climate change. At the global level, potential cereal production in land classified as currently under cultivation increases 4% and 9% for rain-fed multi-cropping and rain-fed and/or irrigated multi-cropping, respectively. *Figure 5.3* presents changes in cereal production potential for three production assumptions (rain-fed single cropping; rain-fed multi-cropping; rain-fed and/or irrigated multi-cropping), showing countries gaining and losing production capacity due to climate change. In order to provide a judicious and more realistic estimate of aggregate climate impacts, changes in national production potentials were scaled in relation to each country's estimated future cereal production requirements, based on a medium-variant population projection for 2080 and assuming

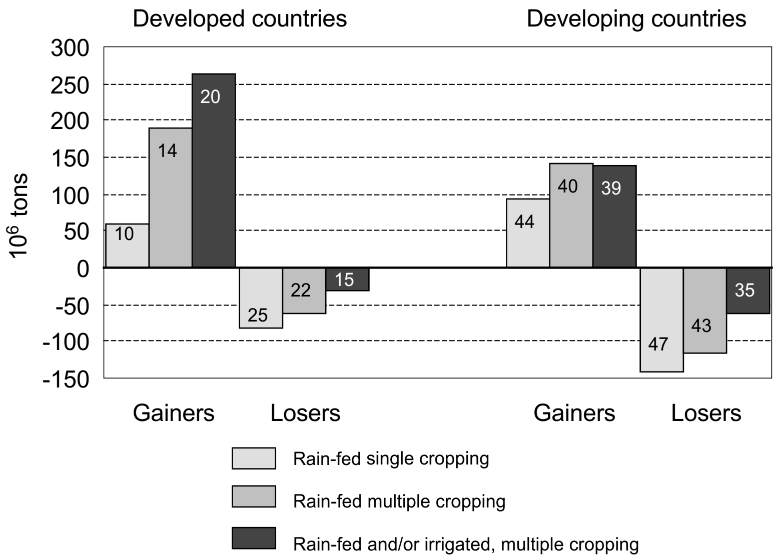

Figure 5.3. Impact of climate change on rain-fed (RF) single cropping, rain-fed multiple cropping (RF_MC), and rain-fed and/or irrigated multiple cropping (RF+IR_MC) cereal production potential on currently cultivated land. Number of countries affected is shown in bars. Gains refer to production increases larger than 5%, losses refer to decreases of 5% or more. The total number of countries is 158, of which 117 are developing and 41 developed. Countries in the range of –5% to +5% are not shown.

an increase of 30% in per capita cereal consumption in developing countries. In other words, when aggregating national-level climate impacts only that share of each country's production potential was counted as necessary to meet the projected consumption requirements.

The aggregate impacts of climate change become more favorable with multiple cropping and with consideration of irrigation. This is illustrated in *Figure 5.3*, especially for developed regions, by the increasing number of gaining countries, the increasing amounts of cereal production potential gained, and the increasing net surplus. The estimated tendency is similar for developing countries, although amounts gained are smaller, amounts lost are larger, and the number of losing developing countries remains high. A comparable picture results from using the climate projections of the CGCM1 model, yet with a rather devastating net balance for developing countries.

Table 5.28 summarizes, for three climate change scenarios, the estimated impacts on "scaled" cereal production potential in current cultivated land under rain-fed conditions, taking into account multi-cropping. It shows that the projected year

Table 5.28. Number of countries, projected year 2080 population, and change in cereal production potential on currently cultivated land of developing countries, rain-fed multiple cropping, 2080s.

Climate	Number of countries			Projected population, 2080 (10^9)			Change in cereal production potential (10^6 tons)			
model	G[a]	N	L	G	N	L	G	N	L	Total
ECHAM4	40	34	43	3.1	0.9	3.7	142	–2	–117	23
HADCM2	52	27	38	3.2	1.2	3.3	207	3	–273	–63
CGCM1	25	26	66	1.1	1.1	5.5	39	3	–268	–226

[a] G = countries gaining +5% or more; N = small change of –5 to +5%; L = countries losing –5% or more.

2080 population in developing countries with potential cereal productivity declines of more than 5% ("losing" countries) ranges between 3.3 to 5.5 billion people. Cereal production losses in these countries are between –117 to –273 million tons, a grim outlook despite the substantial gains in some developing countries, such as China, for example.

Spreadsheet 14 (CD-ROM) presents, by region, impacts of climate change (Max-Planck Institute of Meteorology/ECHAM4 2080s) on rain-fed cereal production potential in current cultivated and all land.

Plate L in this report presents, by grid-cell, the impact of climate change on multiple-cropping cereal production capacity, considering all land with cultivation potential for rain-fed cereals.

The results highlight that climate change will benefit the developed countries more than the developing countries regardless of what is assumed, when considering one rain-fed cereal crop per year or for multiple rain-fed cropping and irrigated production. Also, the results clearly demonstrate that climate impacts will be heterogeneous and vastly different across regions, with the potential of putting major burdens on some 40 to 60 developing countries.

The detailed and spatially explicit results obtained by 5-minute latitude/longitude can be summarized, for instance, by drawing *distributions* of climate impacts on production potential in currently cultivated areas. Six examples are provided in *Figure 5.4*. In each graph, the central bar represents areas where projected climate change results in minor productivity changes of between –5 to +5%. Bars to the right of the center represent areas where impacts are increasingly positive, i.e., +5% to +15%, +15% to +25%, etc., respectively. To the left of the central bar, climate change impacts are increasingly negative, –5% to –15%, –15% to –25%, etc., respectively.

Figure 5.4 illustrates the variety and complexity of outcomes that are to be expected. For instance, while the United States and Russia gain production capacity under a climate change as projected by the ECHAM4 model, even in these countries some areas (and hence farmers) will lose. Another gaining country is China,

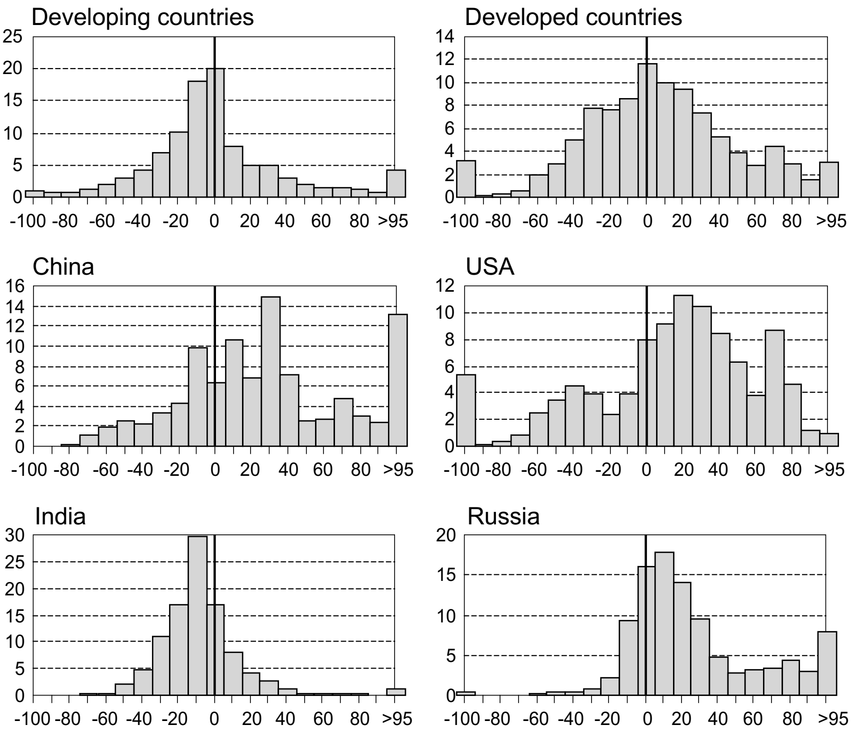

Figure 5.4. Distribution of current cultivated land in terms of climate impacts on cereal productivity, considering multiple cropping under rain-fed conditions, ECHAM4 in 2080s.

though with a widely spread distribution of impacts, and with most cultivated land experiencing significant changes. On the other hand, the example of India shows a rather narrow distribution, with a pronounced median of impacts in the –5% to –15% range, indicating that India would overall be losing food production capacity due to climate change.

In the past, site-specific climate impact studies have produced a wide range of – and even seemingly contradictory – results. While differences in assumptions and methodologies may account for some of the differences, the results obtained in this study clearly demonstrate that a wide range of outcomes is to be expected for many countries, and that a reliable and complete understanding requires a spatially comprehensive approach and analysis such as GAEZ.

Notes

[1] The extents in these tabulations are termed "gross" since we did not subtract land required for other uses, such as infrastructure and settlements, or legally protected areas. In reality, some 10% to 30% of potentially suitable areas may not be available for agriculture due to other competing uses.

[2] The CD-ROM presents, in addition, suitability maps for roots and tubers, pulses, oil crops, sugar crops, and cotton (Plates 31–36).

[3] To obtain representative results for a global study, the 99-percentile of non-zero yields (i.e., the yield level equaled or exceeded by just one 1% of yields) over all grid-cells in the respective climatic zones has been chosen to represent maximum attainable yield potentials.

[4] Net rain-fed land with cultivation potential excludes land requirements for infrastructure. In order to estimate land requirements for housing and infrastructure, we used a gridded population dataset of the year 1995, available from the World Data Center for Human Interaction in the Environment at the Center for International Earth Science Information Network (CIESIN, 2000). The data provide population counts and population density (people per square kilometer) for grid-cells of 5-minute latitude/longitude. Housing and infrastructure requirements amount to 0.1 ha per person in areas with very low population density, and are estimated at 0.05 ha per person when population density is 35 persons per square kilometer, and they decline monotonously to 0.01 ha per person when the density reaches 3,000 persons per square kilometer.

[5] Plate 70 presents a world map with population density in 1995.

[6] Depends on assumptions regarding minimum size of irrigable land tracts considered for irrigation ($SH_{\min}$).

[7] Cereals in GAEZ include: wheat, barley, rye, rice, maize, sorghum, foxtail millet, and pearl millet.

[8] The data set was compiled from remotely sensed multitemporal AVHRR data of 1992/93 by the US Geological Survey (USGS) Earth Resources Observation System (EROS) Data Centre, the University of Nebraska-Lincoln, and the Joint Research Centre (JRC) of the European Commission.

6 Concluding Remarks

This report presents the methodology and results of the GAEZ assessment. The AEZ approach uses a GIS-based modeling framework, which combines land evaluation methods with socioeconomic and multi-criteria analysis to evaluate spatial and dynamic aspects of agriculture. The national- and regional-level information with global coverage enables knowledge-based decisions for sustainable agricultural development.

Results of the GAEZ are estimated by grid-cell and aggregated to country, region, and global levels. They include identification of areas with specific climate, soil, and terrain constraints to crop production; estimation of the extent of rain-fed and irrigated cultivable land and potential for expansion; quantification of cultivation potential for food crops on land currently under forest ecosystems, national and regional impacts of climate change on food production, and geographical shifts of cultivable land and implications for food security.

6.1 Key Findings

- More than three-quarters of global land surface is unsuitable for rain-fed crop cultivation, suffering severe constraints or being too cold (13%), too dry (27%), too steep (12%), or having poor soils (40%). Multiple constraints occur in some locations.
- Cultivable land in the developing countries totals about 1.6 billion ha, of which some 28% is only moderately suitable for crop production. At present, 0.9 billion ha of this land is under cultivation. The corresponding figures for the developed countries are 0.75 billion ha of cultivable land, 47% of which is only moderately suitable, with 0.6 billion ha under cultivation at present. These estimates exclude land required for infrastructure and habitation, closed forests, and legally protected areas.
- In both the developed and the developing world, about 1.4 billion ha constitute forest ecosystems, of which 12% and 30%, respectively, have good potential for crop cultivation. However, cultivation in these forest areas would have severe environmental consequences.
- Intensification of agriculture will be the most likely means to meet the food needs of some 9.3 billion people in 2050. At the global level, the study asserts that enough food can be produced on currently cultivated land if sustainable

management and adequate inputs are applied. However, attaining this situation will require substantial improvements of socioeconomic conditions in many developing countries to enable access to inputs and technology. Several regions exist, where the rain-fed cultivation potential has already been exhausted, as for example is the case in parts of Asia. Land degradation, if continuing unchecked, may further exacerbate regional land scarcities. Concerns for the environment as well as socioeconomic considerations may infringe upon the current agricultural resource base and prevent land and water resources from being developed for agriculture.

- Projected climate change will cause mixed and geographically varying impacts on crop production. Developed countries substantially gain production potential, while many developing countries lose. In some 40 poor developing countries with a combined population of 2 billion, including 450 million undernourished people, production losses due to climate change may drastically increase the number of undernourished, severely hindering progress against poverty and food insecurity.

In essence, the GAEZ assessment has provided a comprehensive and spatially explicit database of crop production potential and related factors. Some examples of recent applications where AEZ or outputs from AEZ analysis have been used for environmental and economic assessments are described below.

6.2 Recent Applications of AEZ

6.2.1 AEZ and impact assessments of climate variability and climate change

Food production systems interact with land and water resources, forest ecosystems, and biodiversity, and climate change will affect these systems both positively and negatively. To enhance and sustain production, it is critical to ensure soil fertility, genetic diversity, agricultural water resource management, and adaptation to the impacts of climate change and variability.

Global warming will affect agro-ecological suitability of specific crops as well as their water requirements. It may also lead to increased pest and disease infestations. The increasing atmospheric concentration of carbon dioxide will enhance plant photosynthesis and contribute to improved water use efficiency. Increased climate variability and extreme events are reported in some countries. In the absence of mitigation and response capacities, losses from damage to the infrastructure and the economy, as well as social turmoil and loss of life, could be substantial. This burden will fall on the poorest in the poorest countries.

The AEZ climate impact assessment is based on a range of projections by various general circulation models, including the ECHAM4 model of the Max-Planck Institute of Meteorology, the HADCM2 model of the Hadley Center for Climate Prediction and Research, and the CGCM1 model of the Canadian Centre for Climate Modelling and Analysis.

GAEZ provides a detailed understanding of the sensitivity of agricultural crops and regional land use systems to climate change. However, the adaptive capacity and vulnerability of national and regional food systems is affected not only by their environmental sensitivity, but also to a large extent by societal factors, notably the socioeconomic conditions of producers and consumers, availability of capital resources, and access to finance and adequate technologies.

An important current step in our research, therefore, is to assess the sensitivity of agro-ecosystems as determined by GAEZ within the socioeconomic context of scenarios defined by the Special Report on Emission Scenarios (SRES) of the IPCC. IIASA's research has provided a framework for analyzing the world food system, viewing national agricultural systems as embedded in national economies, which in turn interact with each other at the international level. The Basic Linked System of National Agricultural Policy Models (BLS) is a world-level general equilibrium model system. It consists of some 35 national and/or regional models. The individual models are linked together by means of a world-market module. We are currently combining the alternative societal pathways of SRES, and their respective emission trajectories and GCM-based climate changes, with the detailed environmental resource databases and assessment methods of GAEZ, to inform and condition the analysis with IIASA's world agriculture model. This approach provides an unprecedented richness and comprehensiveness in assessing food system impacts and vulnerability to climate change.

6.2.2 AEZ and land evaluation for forestry

Combining the AEZ results with spatial forest land cover data revealed that about 237 million hectares of the areas classified as dominantly forest ecosystems were assessed as very suitable or suitable for cultivation. On the other hand, the analysis indicates that, globally, almost 85% of forest ecosystems are not suitable or at best marginally suitable for crop cultivation.

With an increased emphasis on multiple-use forestry, on agro-forestry, on forest as renewable energy source, and on the role of forests in the global carbon cycle, the scope of quantitative land evaluation for forestry is widening. In a recent IIASA study, covering the territory of the former Soviet Union and China, the AEZ evaluation procedures have been extended for the calculation of potential tree biomass. Three different types of forest resources management and exploitation were assumed: (1) conservation forestry aims at nature conservation, bio-diversity preservation, and limited selective extraction of trees; (2) traditional forestry aims at maximizing quality and quantity of timber production; and (3) biomass forestry captures the fully mechanized bio-fuel and pulpwood production for energy generation and industrial application of pulpwood.

6.2.3 AEZ and potentials of fodder and grassland

Among the total of 154 LUTs implemented in GAEZ, there are 13 types concerned with fodder and grass production (six types of silage maize, alfalfa, and six generic types of grasses and pasture legumes). The methodology also includes crop coefficients for quantifying crop residues (e.g., straw) and by-products (e.g., bran from cereals or cakes from processing of oilseeds) potentially available for animal feeding. Together, these provide comprehensive information to assessments of livestock potentials as well as of regional biomass potentials for energy uses from crop and grassland sources.

6.2.4 AEZ and land-use planning

As an extension of basic land productivity assessments, FAO and IIASA have developed AEZWIN, an MS Windows application for use in national and subnational resource planning. When evaluating the performance of alternative LUTs, often the specification of a single objective function does not adequately reflect the preferences of decision-makers, which have a multi-objective nature in many practical problems dealing with resources. Therefore interactive multi-criteria model analysis has been introduced and applied to the analysis of AEZ models. It is at this level of analysis that socioeconomic considerations can effectively be taken into account.

6.2.5 AEZ linkage to economic modeling

The AEZ land productivity assessment provides geographically explicit information that has been embedded within an economic model, to provide a biophysical basis for the estimation of spatially explicit agricultural production relations, and to allow consistent linkage to the modeling of the water sector, in particular the demand for irrigation water. This approach has been developed and tested in a multi-region study of China's agricultural sector.

Agricultural production in this economic model is codetermined by the biophysical potential of land, and by the level of factor inputs (in terms of nutrients and power). Potential output is based on results generated by the AEZ model. The rationale behind this specification is that the observed actual crop output level represents a certain fraction of the biophysical potential. The results obtained in LUC's study on China strongly support the view that it is important to integrate information from biophysical/biological process models within an economic model when analyzing sustainable agricultural development options.

6.2.6 AEZ and food security

The World Food Summit plan of action calls for reducing by half the number of undernourished people in the world. An essential component of this is the need to increase food production, since 75% of the world's poor and hungry live in rural areas and depend directly or indirectly on agriculture for their livelihoods. The integration of the AEZ approach with economic modeling provides a policy analytical frame to set realistic goals and implementation actions for achieving food security at the national and regional levels. In this context, the potential impacts of and adaptation to climate variability and climate change are also being incorporated.

6.2.7 AEZ and Millennium Ecosystem Assessment

The aim of the Millennium Ecosystem Assessment is to examine the processes that support life on earth, like the world's grasslands, forests, rivers and lakes, farmlands, and oceans, and to contribute to improved management and use of the world's natural and managed ecosystems. The combination of AEZ methodology and its spatial resource database, with global coverage, provides an analytical tool for policy making with regard to options for sustainable ecosystem development, including land and water resource use for agricultural production, forest resource management, and other vital functions.

6.3 Limitations of GAEZ

The GAEZ results are based on a half-degree latitude/longitude world climate data set, 5-minute soils data derived from the digital version of the FAO Soil Map of the World, the 30 arc-seconds Global Land Cover Characteristics Database, and a 30 arc-seconds digital elevation data set. While representing the most recent global data compilations, the quality and reliability of these data sets are known to be uneven across regions. The quality of the world soil map, in particular, is reason for concern. It is based on a 1:5,000,000 scale map, and its reliability is generally accepted to vary considerably between different areas. At present, substantial improvements to the soil information are in progress, as for example, the recent global and national soils and terrain digital database (SOTER) updates for South America and the Caribbean, North and Central Eurasia, Northeast Africa, and Eastern Europe.

Another issue is that the current status of land degradation cannot be inferred from the FAO Soil Map of the World. The only study available with global coverage, the Global Assessment of Soil Degradation (GLASOD), compiled by the International Soil Reference and Information Centre (ISRIC) and the United Nations Environment Programme (UNEP), indicates that state and rate of various types of land degradation might very well affect land productivity. However, the GLASOD study itself offers insufficient detail and quantification for useful application within GAEZ.

Socioeconomic needs of rapidly increasing and wealthier populations are the main driving force in the allocation of land resources to various kinds of uses, and socioeconomic considerations are crucial for rational planning of sustainable agricultural development. So far, in GAEZ, the use of socioeconomic information is limited to two elements: spatial distribution of population and the definition of modes of production and the quantification of "input–output packages." The latter are referred to as LUTs, taking to some extent into account the socioeconomic context of production decisions and conditions.

Also the agronomic data, such as the data on environmental requirements for some crops, contain generalizations necessary for global applications. In particular, assumptions on occurrence and severity of some agro-climate-related constraints to crop production would, no doubt, benefit from additional verification and data.

For the above reasons, the results obtained from this GAEZ study should be treated in a conservative manner at appropriate aggregation levels, which are commensurate with the resolution of the basic data and the scale of the study. While various modes have been pursued for "ground-truthing" and verifying results of the GAEZ suitability analysis, there is a need for further validation of results and underlying databases.

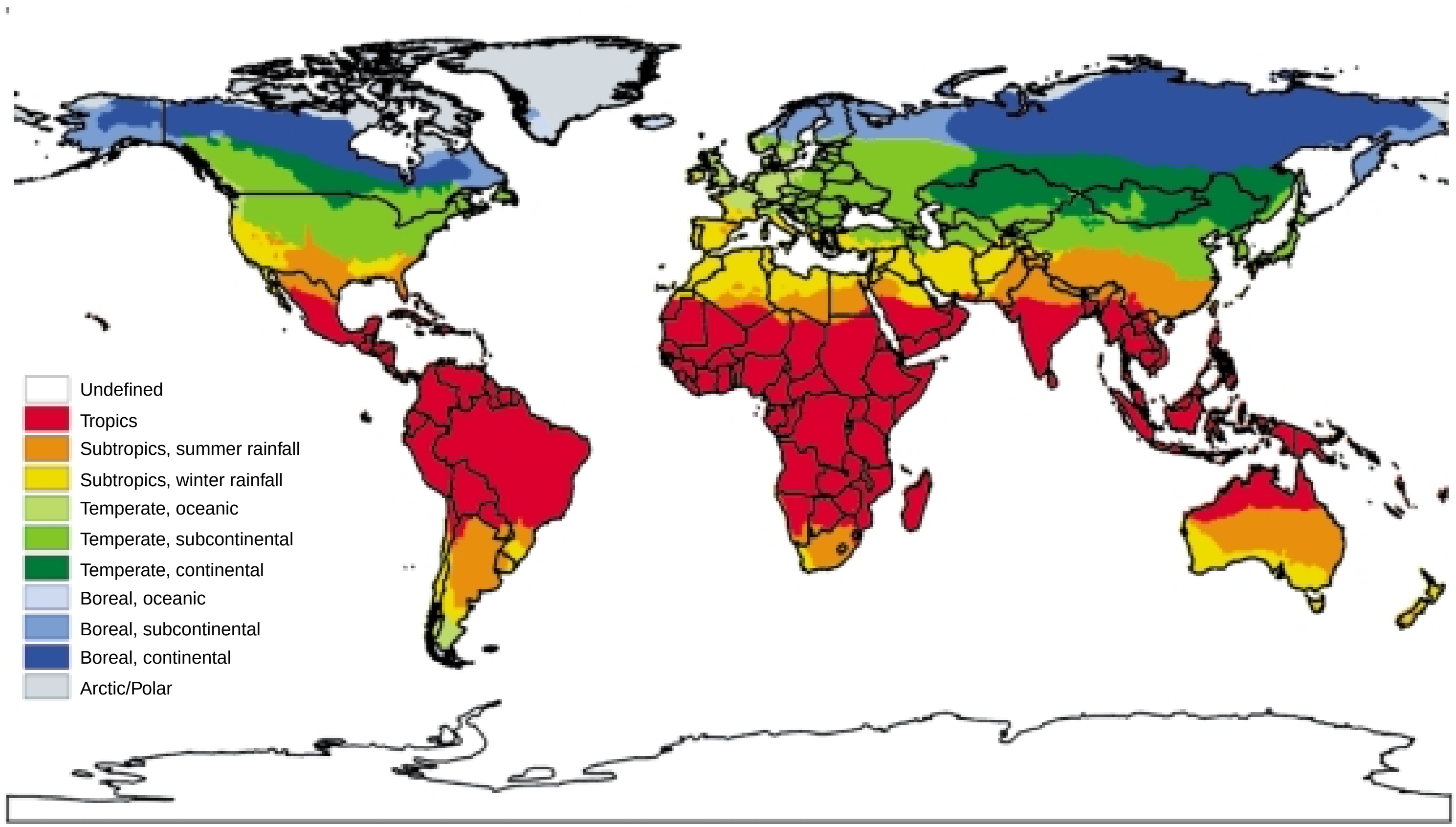

Plate A. Thermal climates.

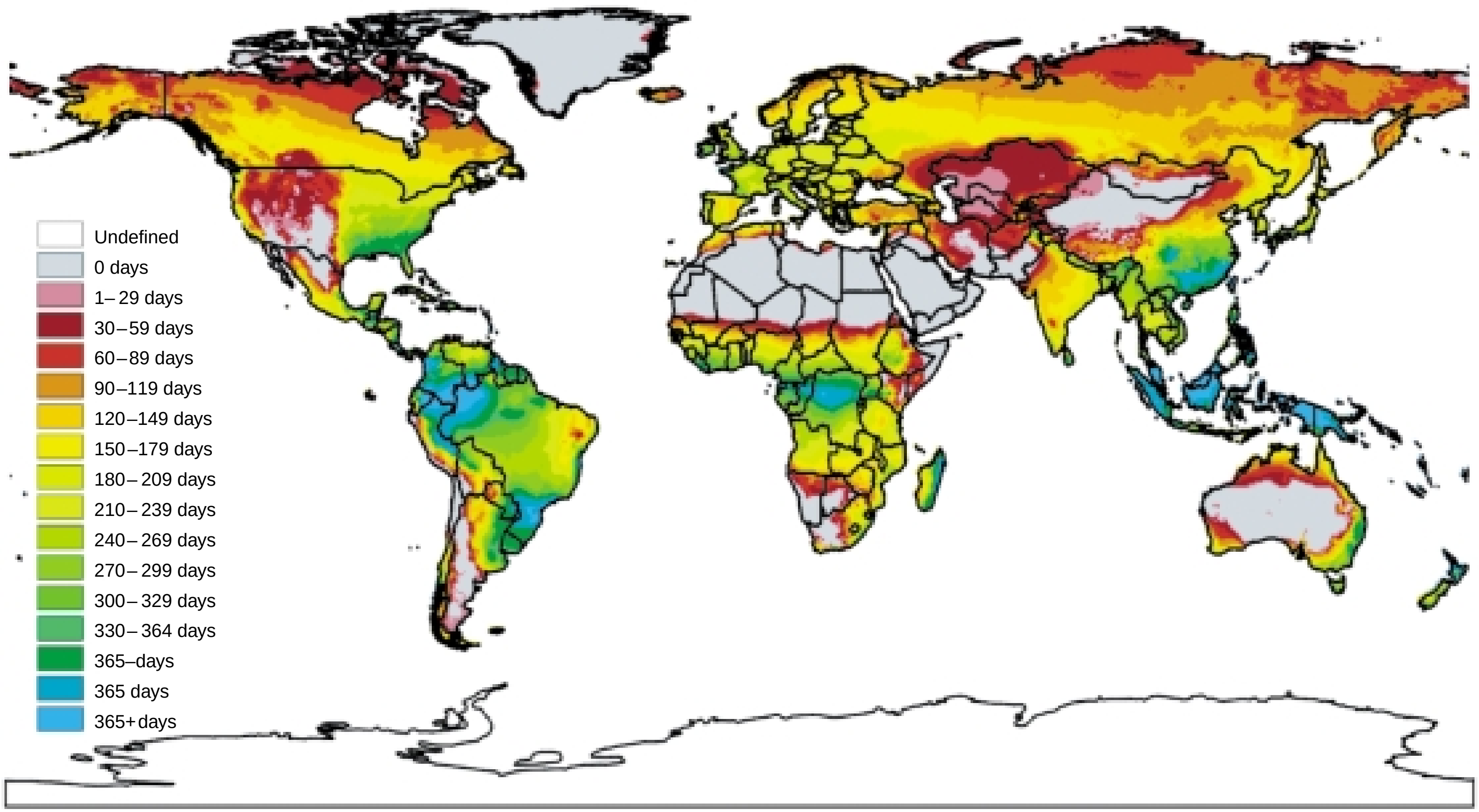

Plate B. Total length of growing periods.

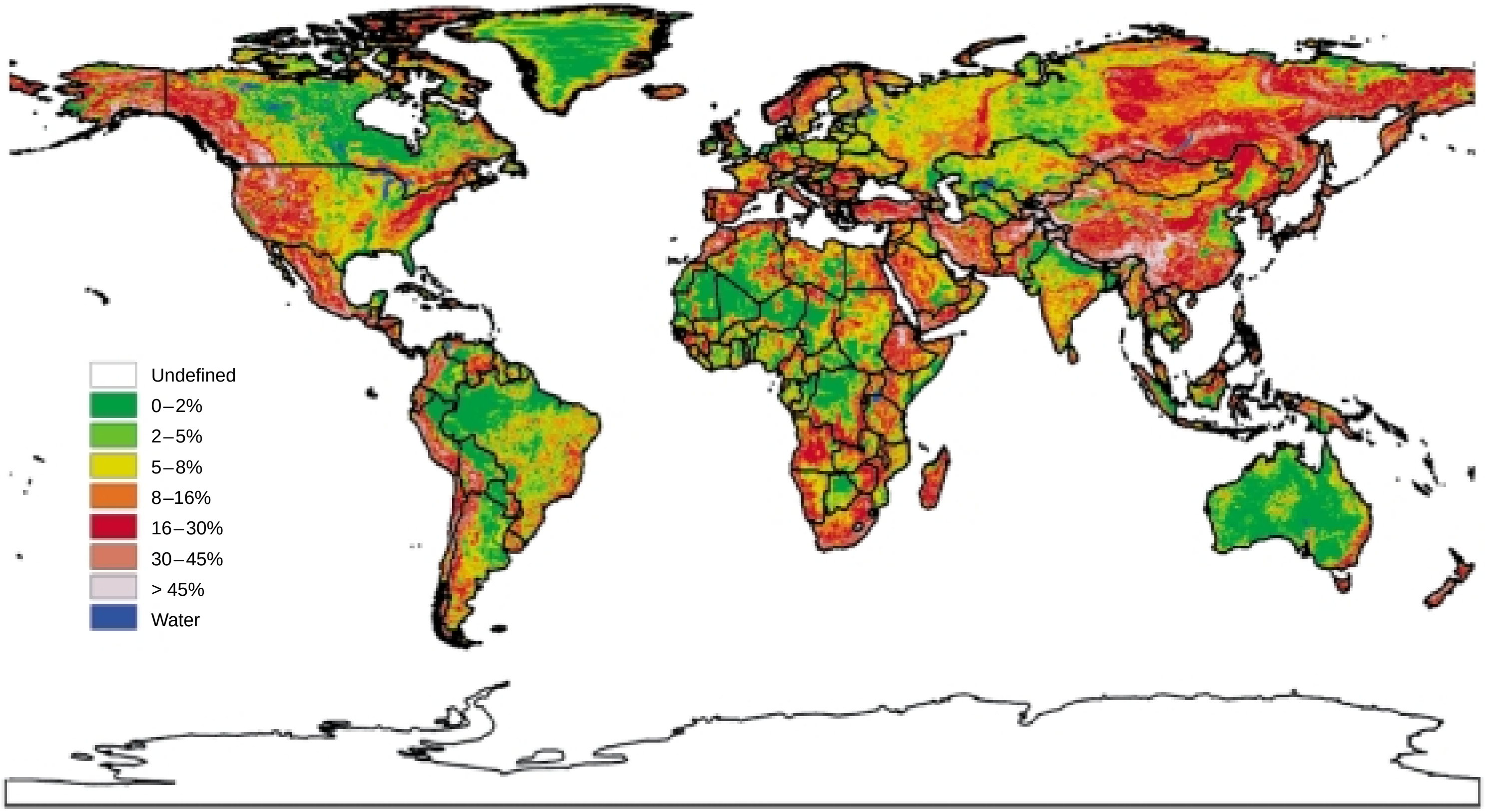

Plate C. Median of terrain slopes derived from GTOPO30.

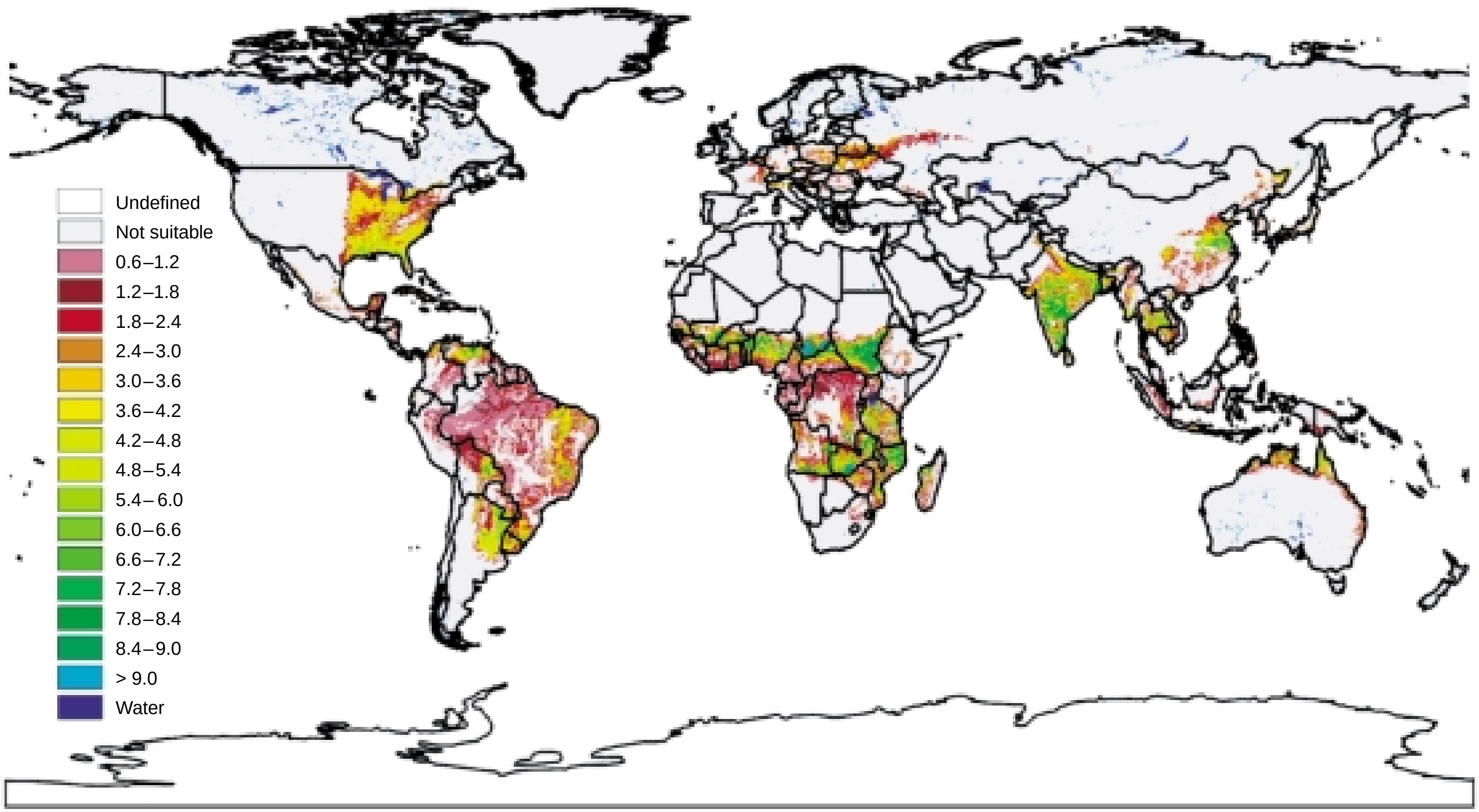

Plate D. Expected grid-cell output[a] per hectare for 120 day rain-fed grain maize (high level of inputs).

[a] Grid-cell output differs from yields; it accounts for per hectare production of total land of individual grid-cells, including not suitable areas.

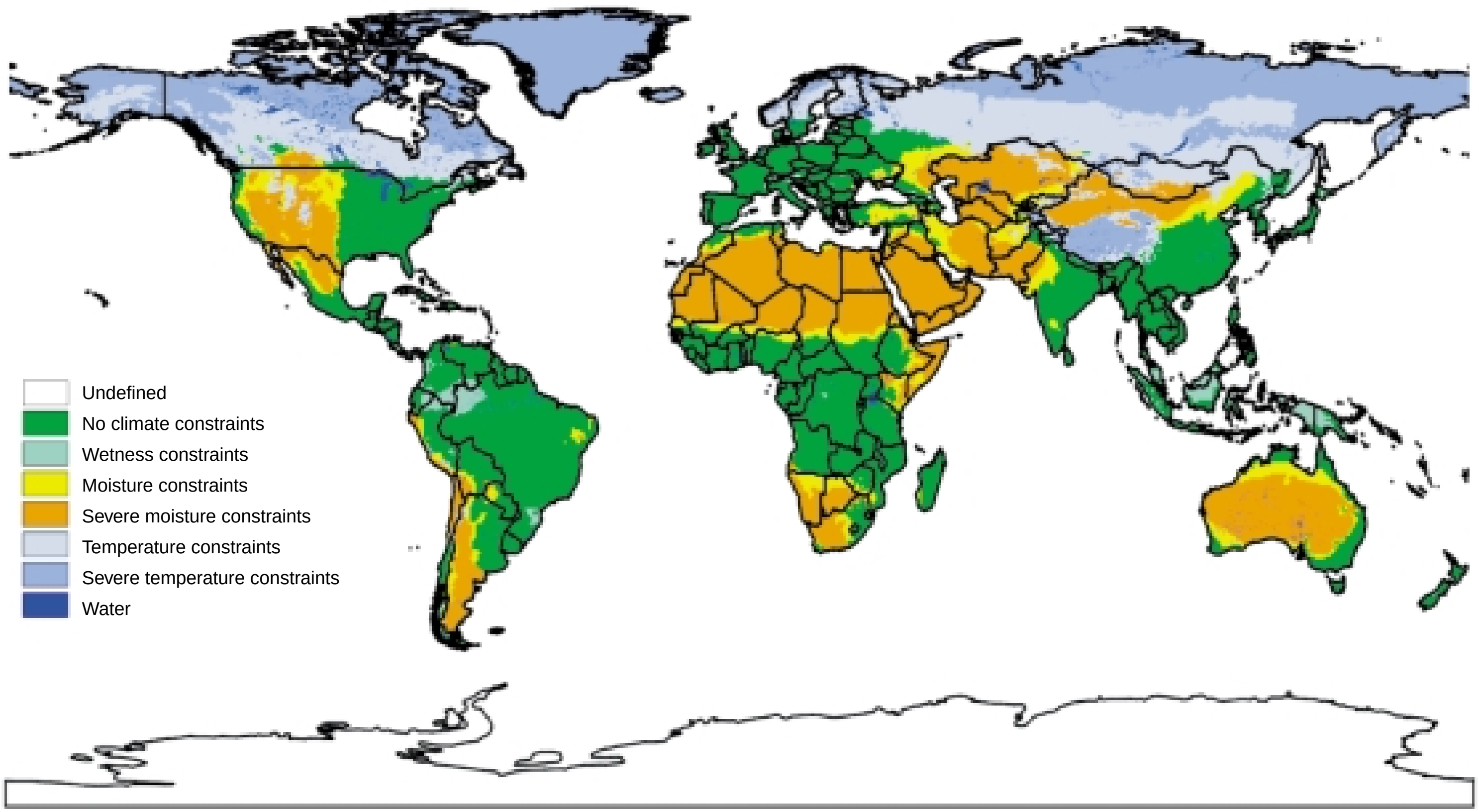

Plate E. Climate constraints.

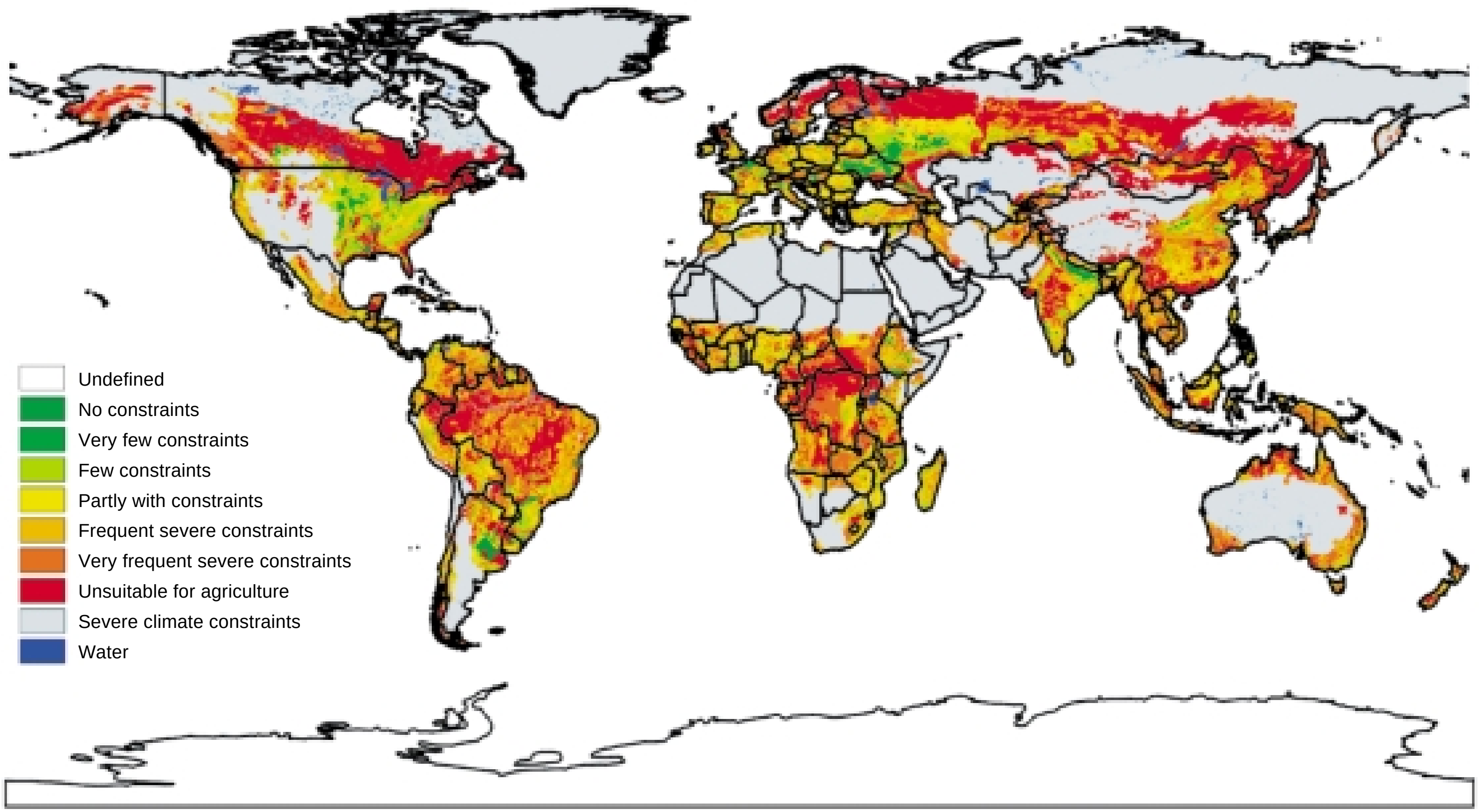

Plate F. Climate, soil, and terrain constraints combined.

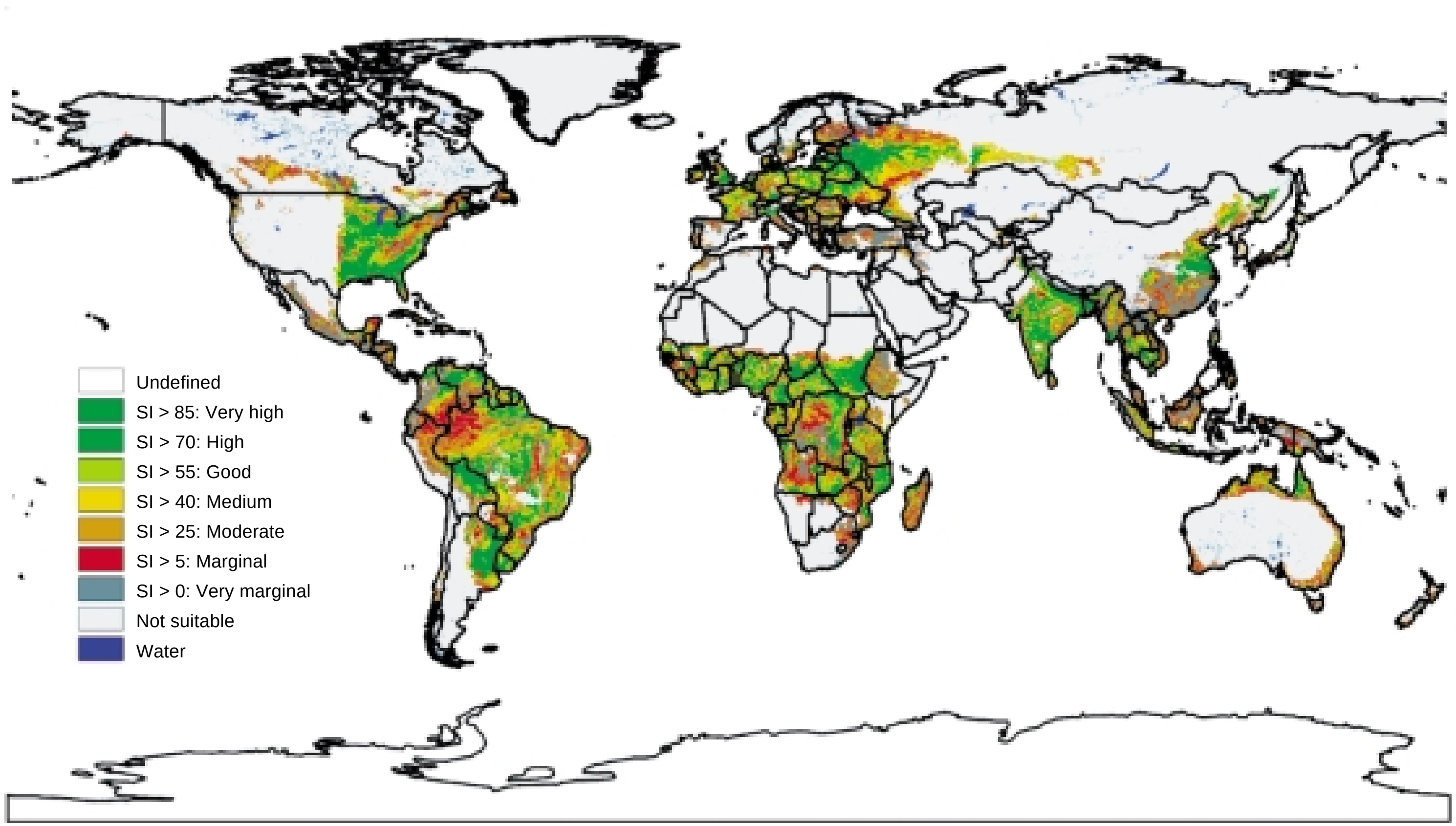

Plate G. Suitability for rain-fed cereals (high level of inputs).

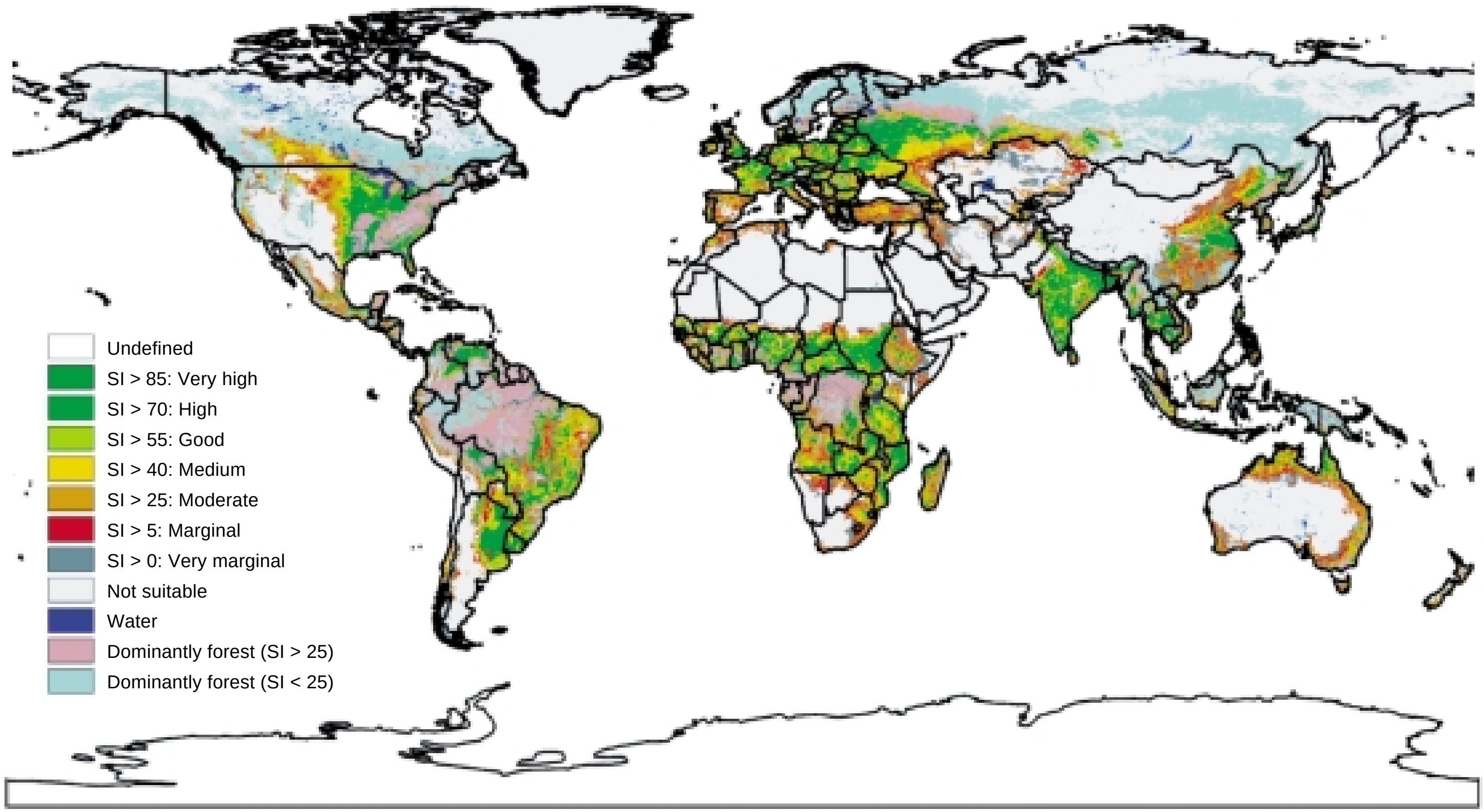

Plate H. Suitability for rain-fed crops (maximizing technology mix).

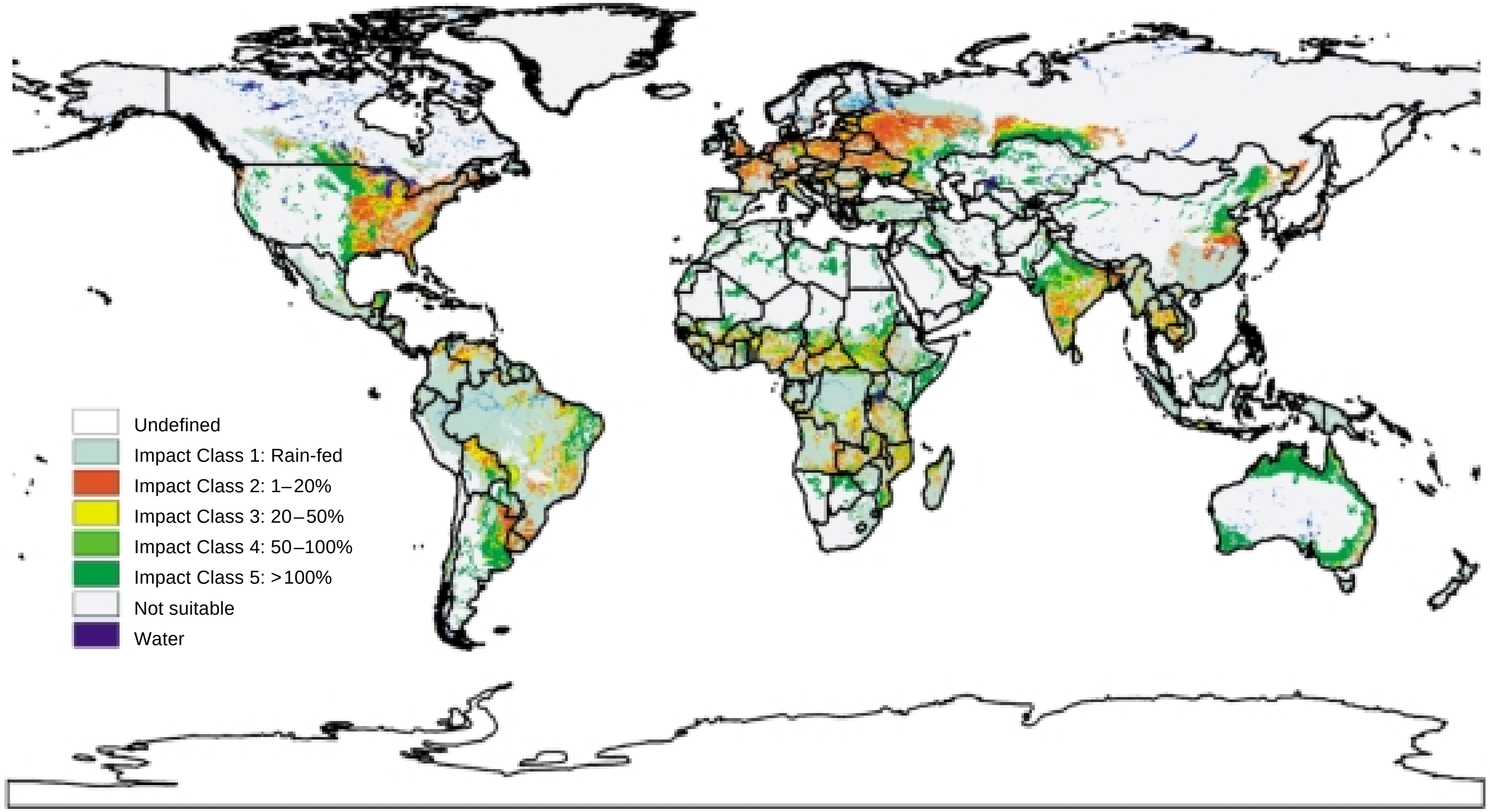

Plate I. Irrigation impact classes.

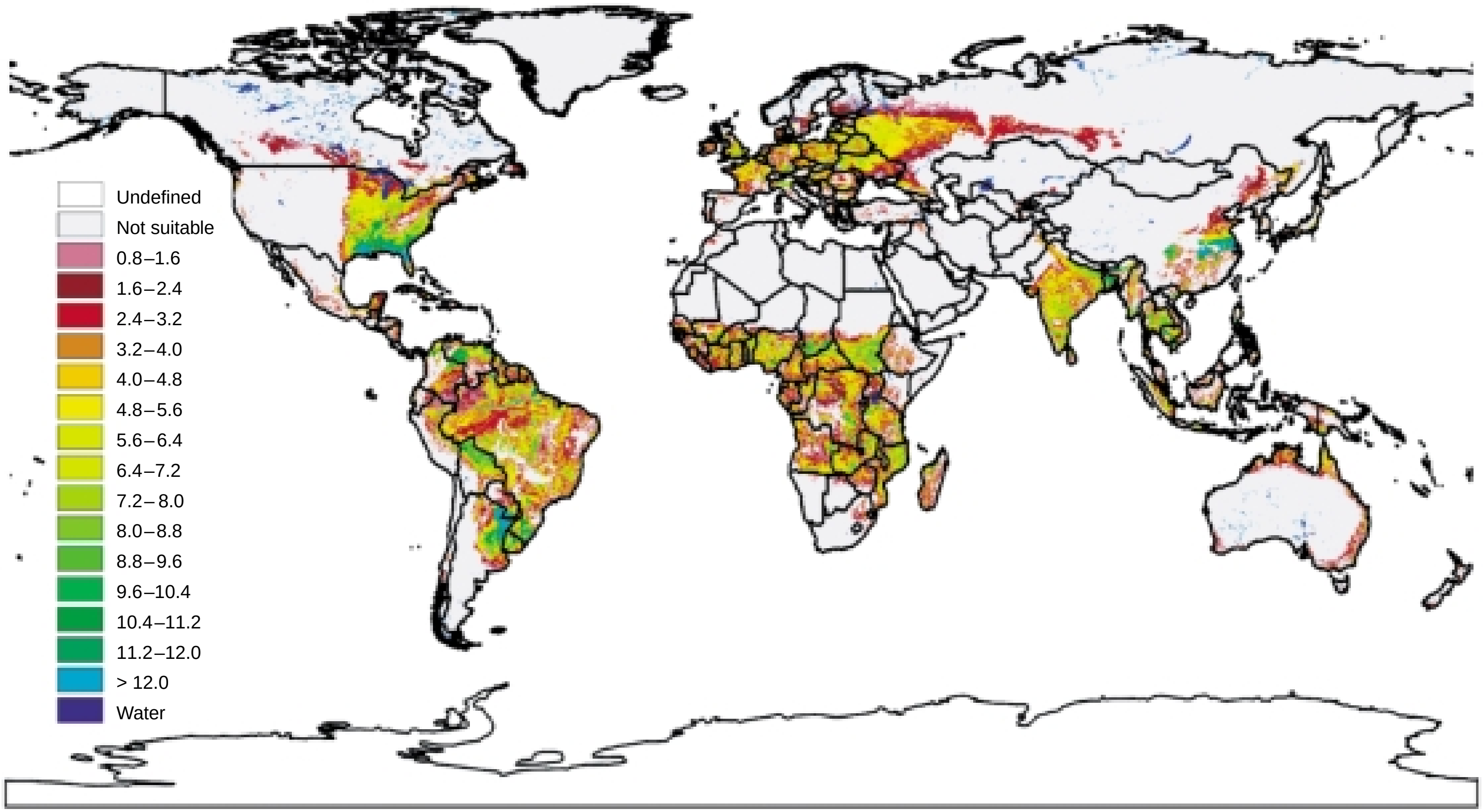

Plate J. Expected grid-cell output[a] per hectare for multiple cropping of rain-fed cereals (high level of inputs).

[a] Grid-cell output differs from yields; it accounts for per hectare production of total land of individual grid-cells, including not suitable areas.

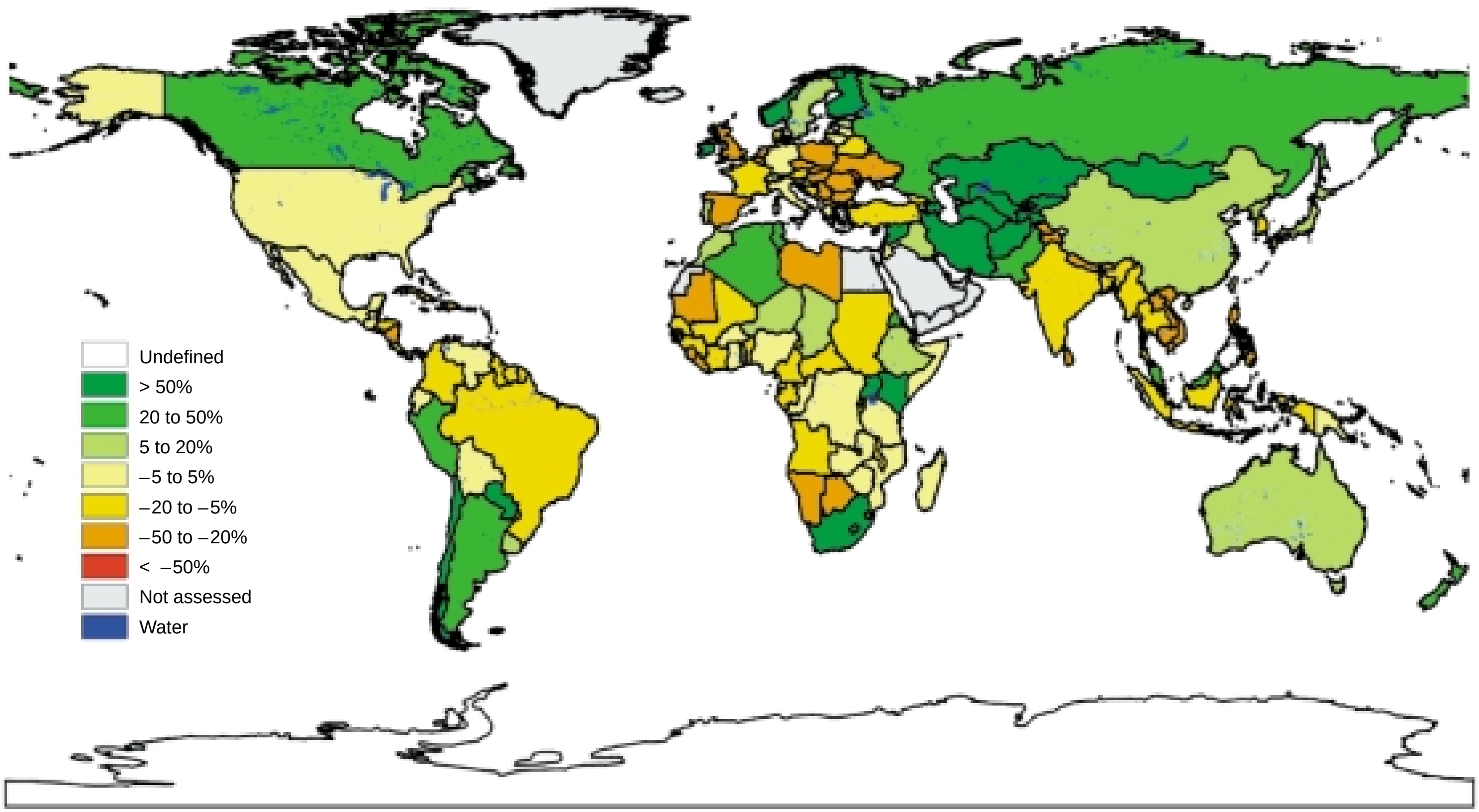

Plate K. Max-Planck Institute of Meteorology/ECHAM4 2080: Country-level climate change impacts on rain-fed cereal production potential on currently cultivated land.

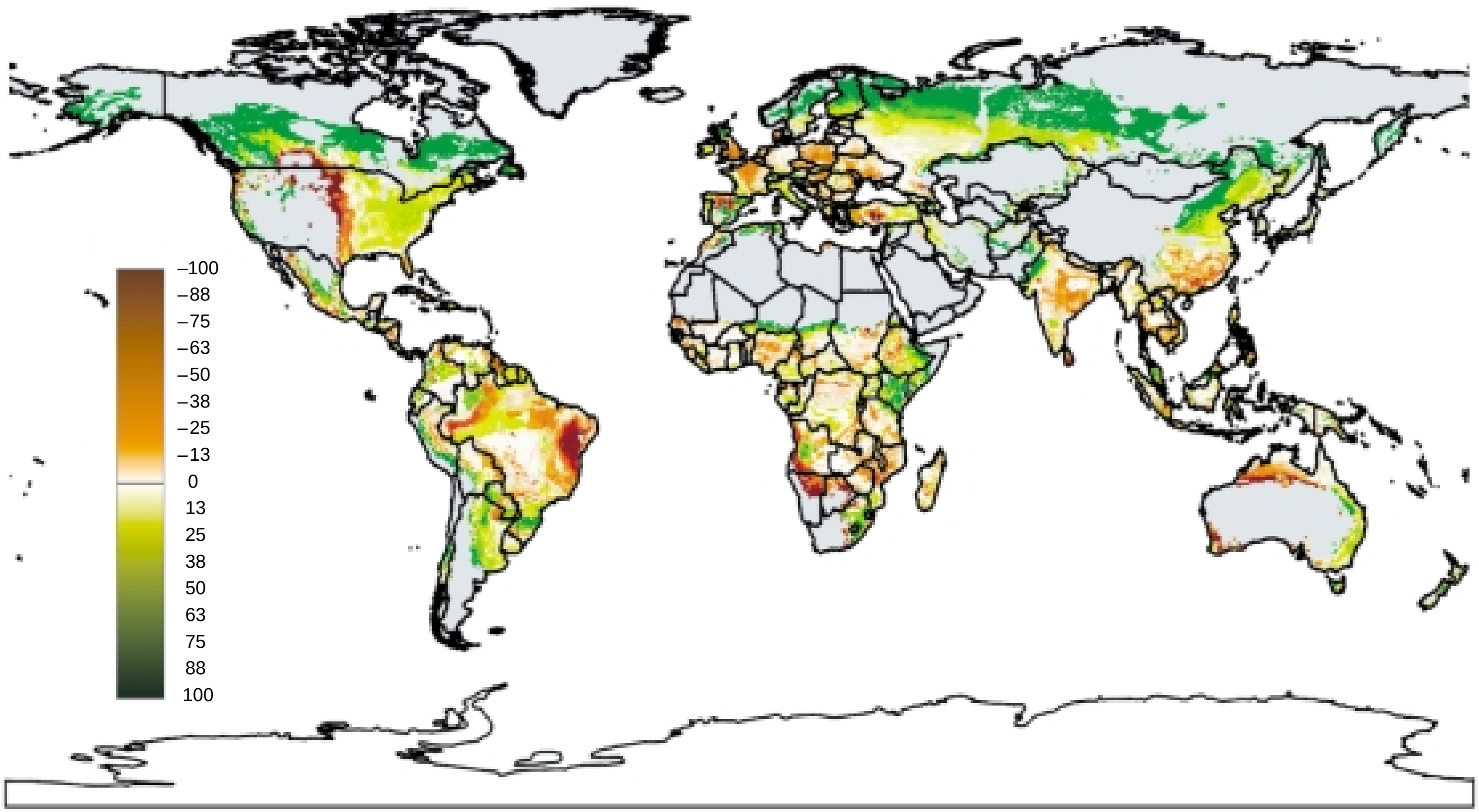

Plate L. Max-Planck Institute of Meteorology/ECHAM4 2080: Impacts of climate change on multiple cropping production potential of rain-fed cereals.

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