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Contents

1. Background
2. Methodology
3. Findings
4. Concluding Remarks
Glossary
Bibliography
Biographical Sketches
To cite this chapter

Summary

This chapter presents a summary of the methodology and results of a comprehensive global assessment of the world's agricultural ecology. The national-level information with global coverage enables knowledge-based decisions for sustainable agricultural development. The Agro-ecological Zones approach is a GIS-based modeling framework that combines land evaluation methods with socioeconomic and multiple-criteria analysis to evaluate spatial and dynamic aspects of agriculture.

The results of the Global AEZ assessment are estimated by grid cell and aggregated to national, regional, and global levels. They include identification of areas with specific climate, soil, and terrain constraints to crop production; estimation of the extent and productivity of rain-fed and irrigated cultivable land and potential for expansion; quantification of cultivation potential of land currently in forest ecosystems; and impacts of climate change on food production, geographical shifts of cultivable land.

1. Background

The Food and Agriculture Organization of the United Nations (FAO), in collaboration with the International Institute for Applied Systems Analysis (IIASA), has developed the Agro-ecological Zones (AEZ) methodology (FAO 1978-81, FAO/IIASA/UNFPA,

1982) and a worldwide spatial land resources database. Together this enables an evaluation of biophysical limitations and production potential of major food and fiber crops under various levels of inputs and management conditions.
When evaluating the performance of alternative types of land use, a single criterion function often does not adequately reflect the decision-maker's preferences, which are of a multiple-objective nature in many practical problems dealing with resources planning. Therefore, interactive multiple-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 a spatial and integrated ecological–economic planning approach to sustainable agricultural development.

Future land uses and agricultural production are not known with certainty. For example, what will be the availability and adoption of agricultural technology for various crops in the future? What new genetic crop varieties will be available? How will climate change affect crop areas and productivity? A scenario approach based on a range of assumptions related to such changes in the future enables assessments and a distribution of outcomes that facilitate policy considerations and decision making in the face of future uncertainty.

The AEZ approach, estimated by grid cell and aggregated to national, regional, and global coverage, provides the basis for several applications. These include the following:

- 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 crop productivity under the assumptions of three levels of farming technology and management.
- Evaluation of land in forest ecosystems with cultivation potential for food crops.
- Regional impact and geographical shifts of agricultural land and productivity potentials and implications for food security resulting from climate change and variability.

A complete description of the methodology, as well as results detailed for regions across the globe, can be found in the IIASA/FAO CD-ROM application (Fischer *et al*, 2000) and IIASA's Research Report on Global Agro-ecological Assessment - Methodology and Results (Fischer *et al*, 2001, 2002).

2. Methodology

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 assumed levels of inputs and management conditions. The elements involved in the AEZ framework are described in Figure 1.

FAO's Digital Soil Map of the World (FAO, 1995) has been made the reference for constructing a land surface database consisting of more than 2.2 million grid cells at 5-minute latitude/longitude within a raster of 2160 rows and 4320 columns. On the input side (Figure 1), the key components of the database applied in the AEZ methodology include the following:

- The FAO Digital Soil Map of the World and linked soil association and attribute databases.
- The Global 30 arc-second Digital Elevation Model (EROS Data Center, 1998) was used for elevation and the derived slope distribution database.
- The global climate data set of the Climate Research Unit of the University of East Anglia (CRU) consisting of average data (for the period from 1961 to 1990) and data for individual years from 1901 to 1996 (New *et al*, 1998).
- A layer providing distributions in terms of 11 aggregate land-cover classes derived from a global 1-kilometer land-cover data set (EROS Data Center, 2000).

The AEZ global land resources database also incorporates spatial delineation and accounting of forest and protected areas. A global population data set for the year 1995 provides estimates of population distribution and densities at a spatially explicit sub-national level for each country.

On the output side, numerous new data sets have been compiled at the grid-cell level and tabulated at the national and regional levels. Outputs include: (1) agro-climatic characterizations of temperature and moisture profiles, and (2) time series of attainable crop yields for all major food and fiber crops.

The AEZ methodology considers the contribution of multiple cropping to land productivity on the basis of the evaluation of thermal and moisture profiles in a grid cell for determination of agronomically meaningful sequential crop combinations.

Figure 1. Agro-Ecological Zones (AEZ) methodology.

The AEZ framework incorporates the following basic elements:

- Selected agricultural production systems with defined input and management relationships, and crop-specific environmental requirements and adaptability characteristics. These are termed "land utilization types" (LUTs). The AEZ study distinguishes some 154 crops, fodder, and pasture LUTs, each at three levels of inputs and management (high, intermediate, low).
- Geo-referenced climate, soil, and terrain data, which are combined into a land resources database. The computerized global AEZ database contains some 2.2 million grid cells.
- Accounting for spatial land use and land cover, including forests, protected areas, population distribution and density, and land required for habitation and infrastructure.
- Procedures for calculating the potential agronomically attainable yield and for matching crop and LUT environmental requirements with the respective environmental characteristics contained in the land resources database, by land unit and grid cell.
- Assessment of crop suitability and land productivity of cropping systems.

- Applications for estimating the land's population supporting capacity, multiple-criteria optimization incorporating socioeconomic and demographic factors of land resource use for sustainable agricultural development.

The AEZ assessments were carried out for a range of climatic conditions, including a reference climate with data on individual historical years, as well as scenarios of a future climate based on various global climate models. Farming technology was considered at three levels: a high level of inputs with advanced management, an intermediate level with improved management, and a low level of inputs with traditional management (Table 1). Hence, the results quantify the impacts on land productivity of both historical climate variability and potential future climate change.

Intensity level	Characteristics
HIGH LEVEL OF INPUTS/ADVANCED MANAGEMENT	Production is based on improved high-yielding varieties and is mechanized with low labor intensity. It uses optimum applications of nutrients; chemical pest, disease, and weed control; and full conservation measures. The farming system is mainly market oriented.
INTERMEDIATE LEVEL OF INPUTS/IMPROVED MANAGEMENT	Production is based on improved varieties and on manual labor and/or animal traction and some mechanization. It uses some fertilizer application and chemical pest, disease, and weed control, and employs adequate fallow periods and some conservation measures. The farming system is partly market oriented.
LOW LEVEL OF INPUTS/TRADITIONAL MANAGEMENT	Production is based on the use of traditional cultivars (if improved cultivars are used, they are treated in the same way as local cultivars) and labor-intensive techniques, with no application of nutrients. It uses no chemicals for pest and disease control and employs adequate fallow periods and minimum conservation measures. The farming system is largely subsistence based.

Table 1. Farming technology.

3. Findings

The AEZ results (Fischer *et al*, 2001a) indicate that, at the global level, Earth's land, climate, and biological resources are ample to meet food and fiber needs of future generations, in particular, for a world population of 9.3 billion, as projected in the United Nations medium variant for the year 2050 (United Nations, 1998). Despite this positive aggregate global picture, however, there are reasons for profound concern in several regions and countries with limited land and water resources.

Socioeconomic development will inevitably infringe on the current and potential agricultural land resource base, as the need to expand industrial, infrastructure, and habitation land use increases. Furthermore, global environmental changes, particularly climate change, are likely to alter the conditions and distribution of land suitability and crop productivity in several countries and regions.

The presentation of results is organized as follows:

- Climate, soil, and terrain limitations to crop production.
- Land with cultivation potential.
- Potential for expansion of cultivated land.
- Cultivation potential in forest ecosystems.
- Yield and production potentials.
- Temperature and rainfall sensitivity.

It should be noted that the AEZ results have been aggregated to the national, regional, and global levels. Furthermore, the farming technology and input assumptions are based on present-day knowledge. Research and scientific developments in the future could alter the projection outcomes.

3.1. Climate, Soil and Terrain Limitations to Crop Production

Climate constraints are classified according to the length of periods with cold temperatures and moisture limitations. Temperature constraints are related to the length of the temperature growing period, i.e. the number of days with a mean daily temperature above 5 °C. For example, a temperature growing period shorter than 120 days is considered a severe constraint, while a period shorter than 180 days is considered to pose moderate constraints to crop production. Hyper-arid and arid moisture regimes are considered severe constraints, and dry semi-arid moisture regimes are considered moderate constraints.

Soil constraints are classified into moderate and severe limitations imposed by soil depth, fertility, and drainage; soil texture/structure/stoniness; and specific soil chemical conditions. Limitations imposed by terrain slope have been classified similarly. The extent of land with climate and soil/terrain constraints is shown in Figure 2.

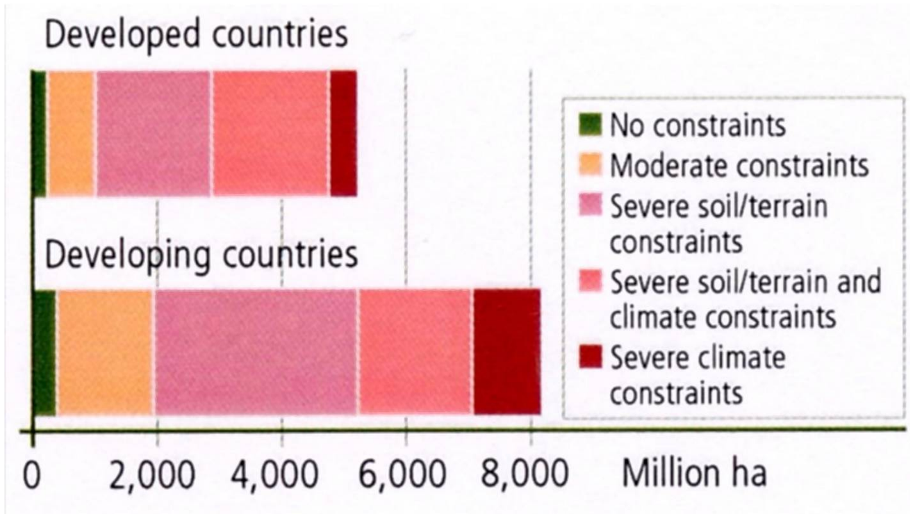

Figure 2. Extent of land with climate and soil/terrain constraints.

On the basis of currently available global soil, terrain, and climate data, the AEZ estimates indicate that 10.5 billion hectares (ha) of land—more than three-quarters of the global land surface, excluding Antarctica—suffer rather severe constraints for rain-fed crop cultivation. Some 13% of the surface is too cold, 27% is too dry, 12% is too steep, and about 65% is constrained by unfavorable soil conditions, with multiple constraints coinciding in some locations. Figure 3 shows the distribution of land constraints by region, and Figure 4 portrays the situation worldwide.

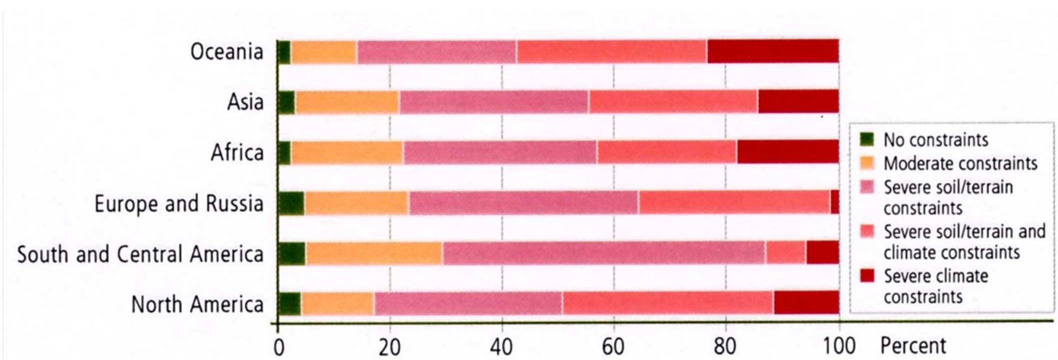

Figure 3. Distribution of climate and soil/terrain constraints by region.

At the global level, almost 40% of the soils suffer from severe fertility constraints and about 6% are affected by limitations resulting from salinity, sodicity, or gypsum constraints. The respective regional figures are 43% and 1% for North America; 46% and 5% for South and Central America; 56% and 4% for Europe and Russia; 30% and 3% for Africa; 28% and 11% for Asia; and 31% and 18% for Oceania.

Climate change is likely to have both positive and negative effects on extent and productivity of arable land resources. In some areas, prevailing constraints may be somewhat relieved by climate change, thus increasing the arable land resources. In other areas, however, currently cultivated land may become unsuitable for agricultural production.

The extent to which specific constraints like low fertility and toxicity can be overcome will also depend on the outcomes of agricultural and scientific research. For example, agricultural research in Mexico has resulted in the application of biotechnology to increase plant tolerance to aluminum, thus countering soil toxicity problems common in some tropical areas.

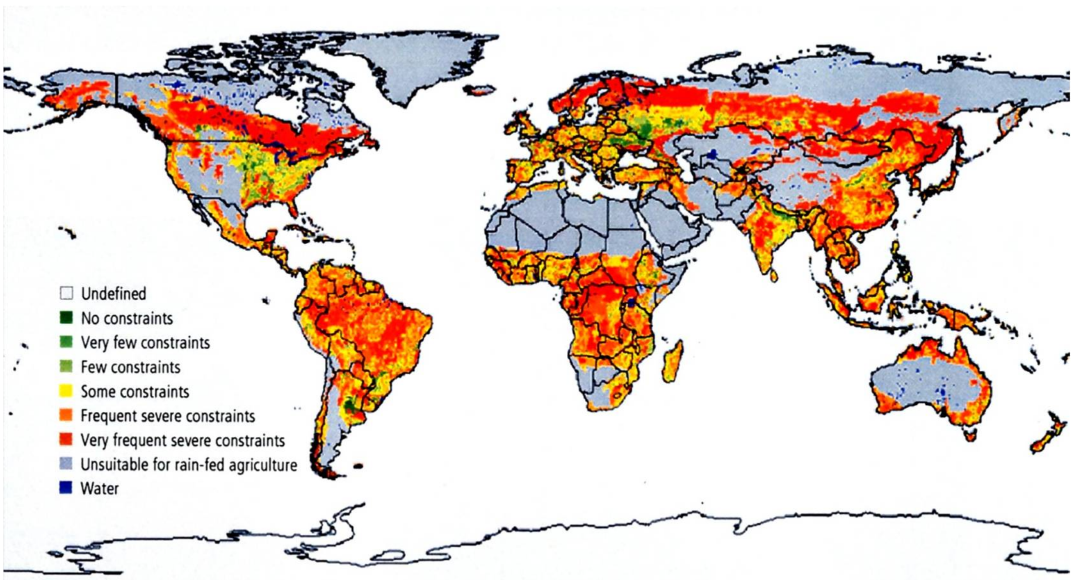

Figure 4. Climate and soil/terrain constraints combined at worldwide level.

3.2. Land with Cultivation Potential

There are various ways to estimate the extent of land with cultivation potential for rain-fed crops. Any quantification depends on a variety of assumptions concerning the range of crop types considered; the definition of what level of output qualifies as acceptable; and the social acceptance of land-cover conversions (of forests in particular) and what land constraints may be alleviated with farming technology, management, and investment.
The AEZ assessment considers a total of 24 crop species, two pasture types, and two fodder crops. Altogether, 154 crop/land utilization types are considered, each at three defined levels of inputs and management.

The results of the estimation of extent of land with cultivation potential for major crops show that at the global level about 2.7 billion ha are suitable for cereal cultivation with a high level of inputs and management, and about three-quarters of this land is very suitable or suitable. The land area suitable for roots & tubers and pulses is some 30% to 40% smaller than that suitable for cereal (Table 2).

Level of inputs	Suitability of land	Cereals	Roots &tubers	Pulses	Oil crops	Sugar crops	Cotton
High	VS+S	2,000	1,145	1,050	1,495	535	440
	VS+S+MS	2,725	1,865	1,720	2,410	1,150	755
Intermediate	VS+S	1,590	795	725	1,105	385	280
	VS+S+MS	2,500	1,515	1,495	2,035	900	580
Intermediate excluding forests, land for settlement and infrastructure,	VS+S	1,255	595	645	890	270	270
	VS+S+MS	1,960	1,130	1,255	1,585	595	550

VS=very suitable; S=suitable; MS=moderately suitable.

Table 2. Extent of land with rain-fed cultivation potential for major crop groups (million ha).

Table 2 also shows that the cultivable land for each of these major groups of crops is reduced by 10% to 20% at the intermediate level of inputs compared with the high level of inputs. The exclusion of land that is in forest ecosystems and land used for settlement and infrastructure would further reduce the cultivable land area for each of these crop groups by a similar proportion.

It should be emphasized that these results indicate the potential area suitable for each of these individual crop groups. In reality, the demand mix for domestic consumption and trade will drive allocation of land to particular crops.

The total extent of potential rain-fed land is estimated for each grid cell. When considering all modeled Global AEZ crop types excluding silage maize, forage legumes, and grasses, mixing all three input levels, and assuming no restrictions for land-cover conversion, the results show that about one-quarter of the global land surface, excluding Antarctica, can be regarded as potentially suitable for crop cultivation.

The total extent of land suitable for at least one crop amounts to some 3.3 billion ha. Of this, about 23% are in land classified as forest ecosystems. If only the very suitable and suitable land area is considered, then the corresponding extent of land is 2.5 billion ha, with some 24% in forest ecosystems (Table 3).

Region	Total land	Cultivated land 1994–1996		Land with cultivation potential				Settlements and infrastructure
				VS+S		VS+S+MS		
		Rain-fed	Irrigated	Total	In forest ecosystems	Total	In forest ecosystems	
Oceania	850	50	3	76	12	116	17	1
Asia	3,113	376	180	406	36	516	47	83
Africa	2,990	185	12	767	114	939	132	26
Europe & Russia	2,259	289	25	328	61	511	97	21
South &	2,049	141	18	697	281	858	346	16

Central America								
North America	2,138	203	22	266	96	384	135	9
Developing countries	8,171	702	208	1,872	433	2,313	527	124
Developed countries	5,228	543	53	669	168	1,012	247	33
World	**13,400**	**1,245**	**260**	**2,541**	**601**	**3,325**	**774**	**156**

VS=very suitable; S=suitable; MS=moderately suitable.

Table 3. Rain-fed cultivated land in 1994–1996 and rain-fed cultivation potential for major food and fiber crops, mixed inputs (million ha).

In developed countries, about one-fifth of the total land has rain-fed cultivation potential. In developing countries, this proportion is slightly less than 30%. The estimate of cultivable rain-fed land potential is more than twice the area reported by the FAO as land actually in use for cultivation in 1994–1996. These AEZ estimates are high, since all land suitable for at least one crop is included in the assessment and crop choice is not constrained by current demand mix. Figure 5 displays the land suitable for rain-fed crops across the world.

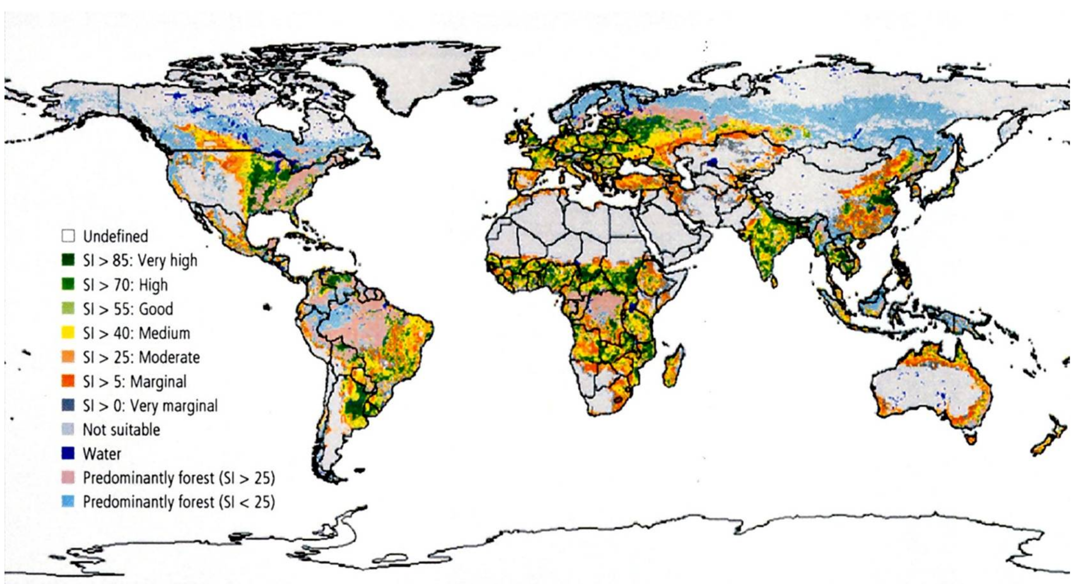

Figure 5. Suitability for rain-fed crops excluding forest ecosystems**.**

For each of the approximately 2.2 million grid cells of the database suitability results were calculated for each crop/LUT. The outcomes were mapped by means of a suitability index (SI). This index reflects the suitability make-up of a particular grid cell. In this index VS represents the portion of the grid cell with attainable yields that are 80% or more of the maximum potential yield. Similarly, S, MS, and mS represent portions of the grid cell with attainable yields 60%–80%, 40%–60%, and 20%–40% of the maximum potential yield, respectively. SI is calculated using the following equation: $SI = VS*0.9 + S*0.7 + MS*0.5 + mS*0.3$

The results highlight that in Asia, Europe, and Russia, the rain-fed land that is currently cultivated amounts to about 90% of the potential very suitable and suitable land. Hence, there is little room for agricultural extensification. In the case of North America, some 75% of the very suitable and suitable land is currently under cultivation. By contrast, Africa and Latin America are estimated to have some 1.1 billion ha of land in excess of currently cultivated land; of this, about 36% is in forest ecosystems. In these two regions there is clearly scope for further expansion of agricultural land, even assuming that current forests are maintained.

3.3. Potential for Expansion of Cultivated Land

Despite the fact that currently reported cultivated land in official statistics is likely to underestimate actual use by some 10 to 20% in several developing countries, the results indicate that there is still a significant potential for expansion of cultivated land in Africa and South and Central America (Figure 6a). More than 70% of additional cultivable (very suitable, suitable, and moderately suitable) land is located in these two regions, and about half of this land is concentrated in just seven countries—Angola, Democratic Republic of Congo, Sudan, Argentina, Bolivia, Brazil, and Colombia. In other regions, this potential is either very limited, as in Asia, or is unlikely to be used for agriculture in the future, as is the case in Europe and Russia, North America, and Oceania (Figure 6b).

Agronomic suitability is by no means the only determinant of future land development. The potential expansion of cultivable land will be limited by the constraints of ecological fragility, degradation, toxicity, and incidences of diseases, as well as by a lack of infrastructure and limited financial resources. These issues will need to be considered explicitly in agricultural intensification at the national level.

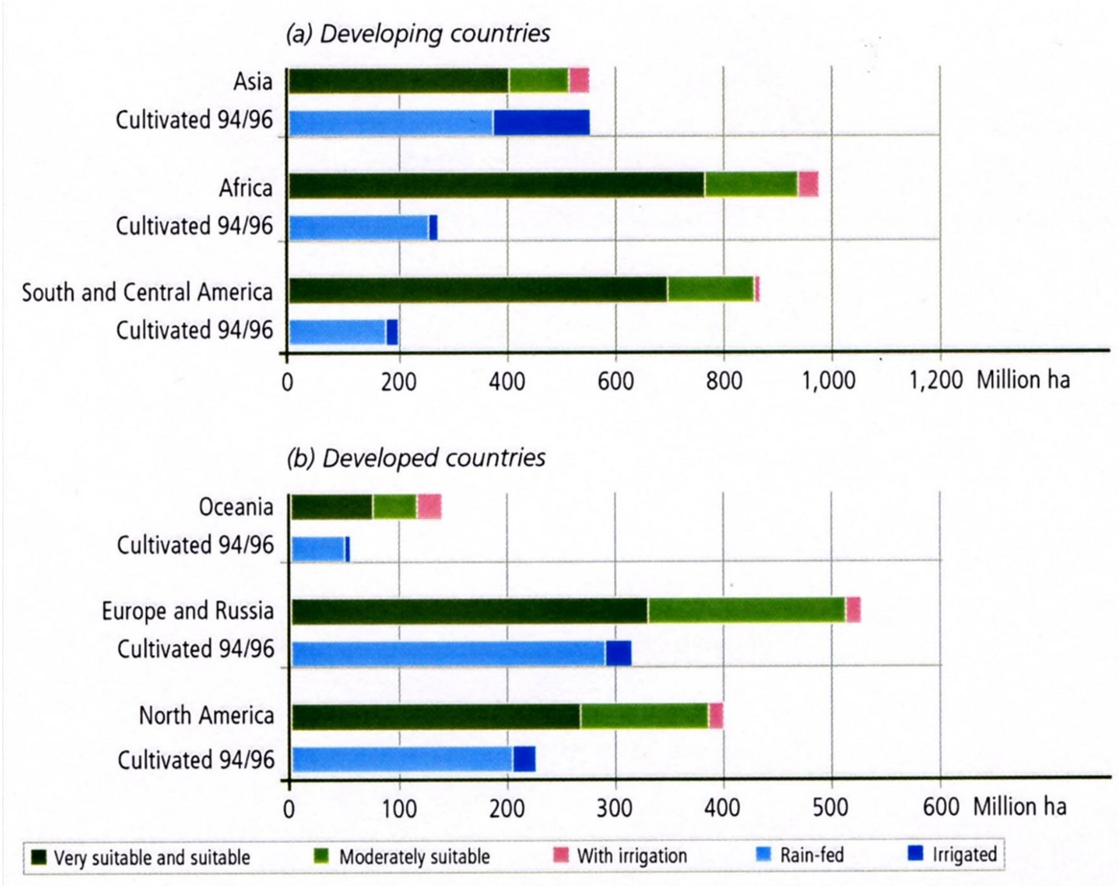

Figure 6. Comparison of land with crop production potential and land used for cultivation in 1994–1996.

3.4. Cultivation Potential in Forest Ecosystems

The FAO Global Forest Resource Assessment 2000 (FAO, 2000) has mapped land area currently in closed forest ecosystems to be 2.9 billion ha, occupying some 21% of the world's land area. In addition, there are some 1.5 billion ha in open and fragmented forest ecosystems.

Russia and Brazil, which account for 19% of the total land area and 5.2% of the world population, have 36% of the global forest areas. The USA and Canada have some 470 million ha of forest, equivalent to 12% of the global forest areas. China, Australia, the Democratic Republic of Congo, and Indonesia account for a further 15% of forestland. These eight countries account for more than 60% of the total forest area in the world.

During the past decade, 127 million ha of the world's forest areas were cleared, while some 36 million ha of forest were replanted. China reported replanting about 50% of this gain. Europe, Russia, and the USA accounted for 24% of it. But Africa lost about 53 million ha of forest during this period.

The loss of forestland in most countries is primarily due to the expansion of crop cultivation. In some areas this is the result of population pressure for more arable land. In other places, like Brazil, commercial agriculture and livestock production are encroaching on forestland. Commercial logging of timber has also contributed to loss of forestland.

In the AEZ assessment, the cereal cultivation potential in forest areas reveals that some 470 million ha of land with cultivation potential for wheat, rice, or maize coincide with land classified as predominantly forest ecosystems, and this accounts for some 19% of land suitable for at least one of the three cereals (Table 4 and Figure 7).

Region	**Total land**	**Total land in forest ecosystems**	**Land with rain-fed cultivation potential**			
			VS+S		**VS+S+MS**	
			Total	**In forest ecosystems**	**Total**	**In forest ecosystems**
Oceania	850	72	44	7	73	11
Asia	3,113	388	263	14	384	25
Africa	2,990	246	404	25	592	43
Europe & Russia	2,259	761	282	41	463	76
South & Central America	2,049	751	283	128	474	200
North America	2,138	562	235	82	342	115
Developing countries	8,171	1,405	1,076	166	1,574	266
Developed countries	5,228	1,381	565	132	884	204
World	**13,400**	**2,786**	**1,612**	**298**	**2,429**	**470**

VS=very suitable; S=suitable; MS=moderately suitable.

Table 4. Land with rain-fed cultivation potential for wheat, rice, or maize in forest ecosystems (million ha).

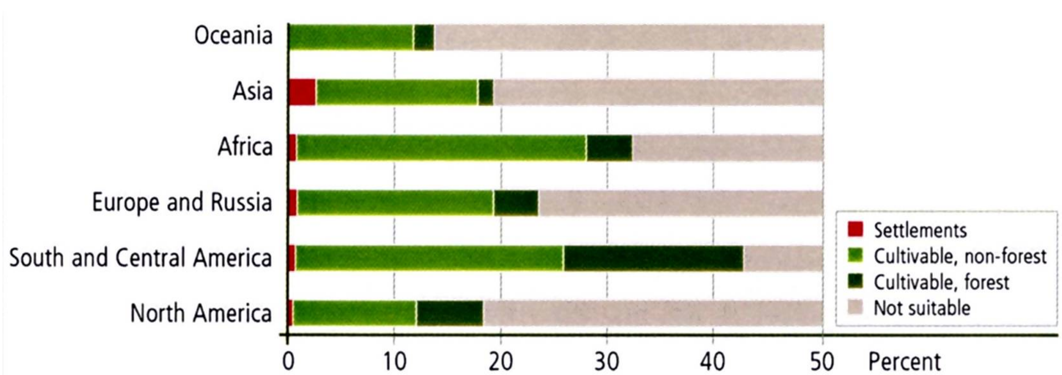

Figure 7. Share of total land suitable for crops, by forest and non-forest area.

Rather wide variations occur between regions. In Russia, for example, less than 9% of the land predominantly in forest ecosystems was assessed to have cultivation potential for cereal crops. Yet, this equates to about a quarter of Russia's land with rain-fed cultivation potential. In South America, these figures are 27% and 35%, respectively, and in North America they are 20% and 39%, respectively.

Considering only the most suitable land in forest ecosystems, about 298 million ha are classified as very suitable or suitable for cultivation of wheat, rice, or maize with mixed levels of inputs. About 44% of this land is located in South and Central America, and altogether some 56% is located in the developing countries.

The spatially quantified information on the productive value of forest areas in terms of (1) potential values of crop and wood production, (2) the conservation role of forests in watershed management and flood control, and (3) their importance as carbon sinks and as habitats of rich biodiversity, is relevant in national considerations concerning the use and conservation of forest areas. These issues need to be central in international negotiations on preservation of regional forest ecosystems in the world.

3.5. Yield and Production Potentials

The maximum attainable yields in the AEZ assessment (Table 5) represent average values from simulated year-by-year agro-climatic yields during the period from 1960 to 1996. These yields were calculated for rain-fed and irrigated cultivation in the tropics, subtropics, and temperate/boreal zones.

	Input level	**Region**	**Crop**		
			Wheat	**Rice**	**Maize**
Rain-fed	Low	Tropics	2.7	5.0	5.1
		Subtropics	4.3	4.7	5.8
		Temperate	4.9	4.9	5.3
	Intermediate	Tropics	5.7	7.7	8.5
		Subtropics	8.4	7.3	8.9
		Temperate	8.7	6.9	8.7
	High	Tropics	8.5	9.9	12.5
		Subtropics	11.8	9.2	12.3
		Temperate	12.1	8.6	12.1
Irrigated	Intermediate	Tropics	7.4	9.5	10.5
		Subtropics	10.2	9.9	12.2
		Temperate	9.7	8.7	11.3
	High	Tropics	11.1	12.2	15.6
		Subtropics	14.2	12.7	17.1
		Temperate	13.5	10.9	15.7

Table 5. Maximum attainable yields under rain-fed and irrigated conditions (tons/ha).

Long-term yields, also estimated using AEZ procedures, assume that proper cycles of cropping and fallow are respected. At high levels of inputs with balanced fertilizer applications and proper pest and disease management, only limited fallow periods will be required. At low levels of inputs—assuming virtually no application of chemical fertilizer and only limited organic fertilizer, and very limited or no application of biocides—considerable fallow periods are needed in the crop rotations to restore soil nutrient status and to break pest and disease cycles.

The yields attained in the long term, when accounting for fallow period requirements, are well below the estimated short-term maximum attainable yields. Required fallow periods vary with soil and climate conditions. On average, long-term yields are 10%, 20%, and 55% lower than maximum attainable yields at high, intermediate, and low levels of inputs, respectively (Table 6). It should also be noted that there is a more than threefold increase in short-term attainable yield and a sevenfold increase in long-term attainable yield in all regions as farming technology and management increases from low to intermediate levels of inputs. At the high level of inputs, the yield level increases further—by 60% to 80%. These estimates for low, intermediate, and high levels of inputs reflect present knowledge and technology.

Intensification of agriculture will be the main means to increase production. In many developing countries, provided adequate inputs and improved management are applied, there is considerable scope for increased yields. For example, in the developing countries the 1995–1997 actual yields per ha for wheat averaged about 1.8 tons for rain-fed conditions and 3.1 tons with irrigation, with an overall average of 2.4 tons per ha, compared with 3.1 tons per ha for major developed country exporters.

Currently there is a wide variation in the level of inputs (e.g. fertilizer application) across regions. In sub-Saharan Africa, an average of 8 kg of nutrients are applied per ha, whereas in other developing countries the rate is about 80 kg of nutrients per hectare, and in the developed countries over 200 kg of nutrients are applied per hectare. These figures are overall averages and include both rain-fed and irrigated crop production. There is considerable scope for improved management and use of inputs—particularly of nutrients—in many developing countries, especially in Africa and South America, where the levels of application are low.

Region	**Low inputs**		**Intermediate inputs**		**High inputs**	
	Short-term attainable	**Long-term sustainable**	**Short-term attainable**	**Long-term sustainable**	**Short-term attainable**	**Long-term sustainable**
Oceania	0.7	0.4	3.2	2.6	5.3	4.8
Asia	1.1	0.5	3.7	3.0	6.2	5.6
Africa	1.1	0.4	3.8	3.1	6.7	6.0
Europe & Russia	0.9	0.4	3.6	2.9	5.5	5.0
South & Central America	1.2	0.6	3.6	3.0	5.6	5.1
North America	0.8	0.4	3.6	2.8	5.8	5.2
Developing countries	1.1	0.5	3.7	3.0	6.2	5.6

Developed countries	0.9	0.4	3.5	2.8	5.6	5.1
World	**1.0**	**0.5**	**3.7**	**3.0**	**6.0**	**5.4**

VS=very suitable; S=suitable; MS=moderately suitable.

Table 6. Maximum short-term attainable and long-term sustainable yields for rain-fed wheat, rice, or grain maize averaged over all VS+S+MS land, by region and level of inputs (tons/ha).

The environmental implications of increasing fertilizer and chemical inputs in the future will have to be taken into account, along with the lessons and experiences from the green revolution. Also, any strategy for increasing food production through intensification must consider the socioeconomic issues of small and resource-poor farmers—in particular, their access to and ability to purchase inputs.

In areas where growing periods are sufficiently long, the AEZ methodology takes into account viable sequential cropping. To perform this estimation, a multiple-cropping zone classification is used to determine feasible crop combinations. The algorithms used for constructing cropping patterns have been designed to ensure that typical crop sequences in cultivation cycles are used. For instance, in the typical double-cropping areas around Shanghai in China, rice or maize was selected as the most productive summer crop, and wheat or barley was chosen as the winter crop. Figure 8 shows the occurrence of multiple-cropping zones worldwide.

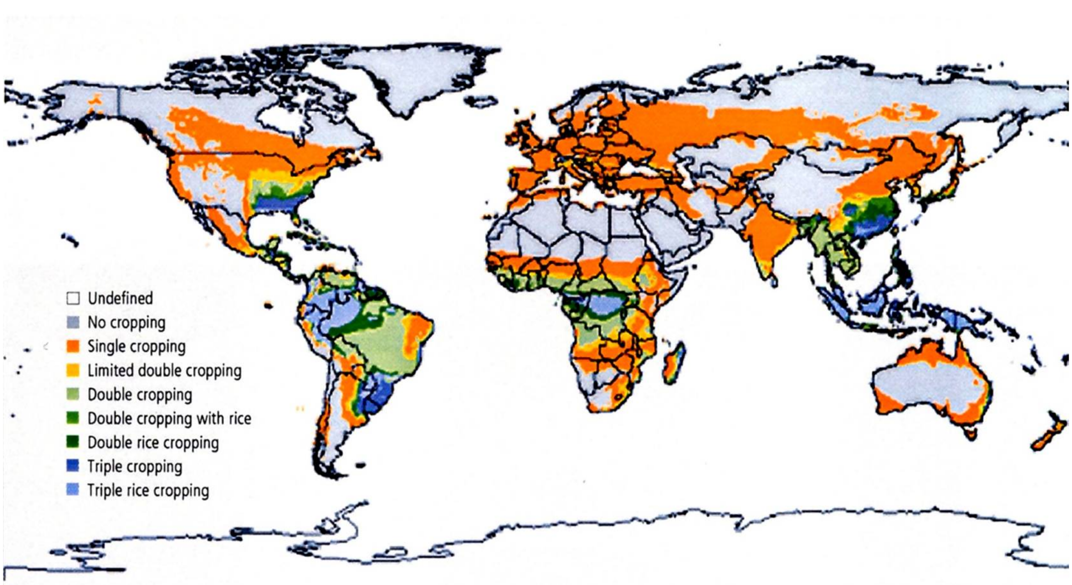

Figure 8. Multiple-cropping zones under rain-fed conditions.

The potential area allowing double or triple cropping of rain-fed cereals is limited in the developed world. In Europe and Russia, it is virtually non-existent. In the developing world as a whole, about 55% of the land with the potential for rain-fed cultivation of cereals is suitable for double or triple cropping. In South and Central America it exceeds 80%: 65% for double and 17% for triple cropping (Table 7).

Region	**Total suitable**	**Single cropping**	**Double cropping**	**Triple cropping**
	(million ha)	**(%)**	**(%)**	**(%)**
Oceania	87	83	13	4
Asia	366	63	32	5
Africa	678	59	39	2
Europe & Russia	422	100	<1	0
South & Central America	606	19	65	17
North America	297	57	30	13
Developing countries	1,645	45	47	8
Developed countries	811	82	13	5
World	**2,455**	**57**	**36**	**7**

Table 7. Share of cultivable land suitable for multiple cropping of rain-fed cereals at intermediate levels of inputs.

3.6. Temperature and Rainfall Sensitivity

Global warming will lead to higher temperatures and changes in rainfall, and this in turn will modify the extent and productivity of land suitable for agriculture. The application of a set of temperature and rainfall sensitivity scenarios revealed a modest increase of cultivable rain-fed land for temperature increases up to 2 °C on a global scale. If temperature increases further but precipitation patterns and amounts remain at current levels, the extent of cultivable rain-fed land starts to decrease. When both temperature and rainfall amounts increase, the extent of cultivable rain-fed land increases steadily. For example, a temperature increase of 3 °C paired with a rainfall increase of 10% would lead globally to about 4% more cultivable rain-fed land. These figures are presented in Table 8.

Region	**Temperature increase**			**Temperature increase and rainfall change**			
	+1°C	**+2°C**	**+3°C**	**+1°C, +5%**	**+2°C, +5%**	**+2°C, +10%**	**+3°C, +10%**
Oceania	–4	–5	–9	1	0	4	0
Asia	4	3	–2	5	2	4	0
Africa	–4	–8	–12	–4	–8	–8	–13
Europe & Russia	13	17	20	16	21	24	28
Central America	–1	–4	–9	–4	–6	–9	–13
South America	–4	–11	–20	–7	–13	–14	–23
North America	12	16	20	16	21	24	28
Developing countries	–1	–6	–11	–2	–6	–6	–11
Developed countries	11	15	18	15	19	22	25
World	**4**	**3**	**1**	**5**	**5**	**6**	**4**

Table 8. Climate sensitivity of land suitable for cereal production (percentage change).

In the developed countries this increase is markedly higher, exceeding 25%. In contrast, the developing countries would experience a decrease of 11%, which could have serious consequences for food security in a number of poor developing countries in Africa, Asia, and South and Central America.

4. Concluding Remarks

4.1. Prospects

The present study has outlined various applications where biophysical assessments based on the AEZ methodology can substantially contribute to effective resource use for sustainable agricultural development. While improvements of the basic methodology and data are a general aim, the planned work is concerned with regional applications and case studies.

The AEZ approach combined with socioeconomic modeling provides an integrated tool for sustainable land-use planning and resource development at the sub-national and national levels. To date, several regional and more than 20 country studies have been undertaken (Figure 9). It is envisaged that the methodology and the results in this first Global AEZ assessment will catalyze many more detailed studies, particularly at the regional and national levels such as:

- Analysis of impacts of climate variability and climate change on agricultural production.
- Inclusion of water resources data and modeling to enhance the assessment of irrigation production potentials at watershed level.
- Application of AEZ multiple-criteria analysis of a geographically explicit environmental and socioeconomic database to enhance formulation of alternative rural development policies.

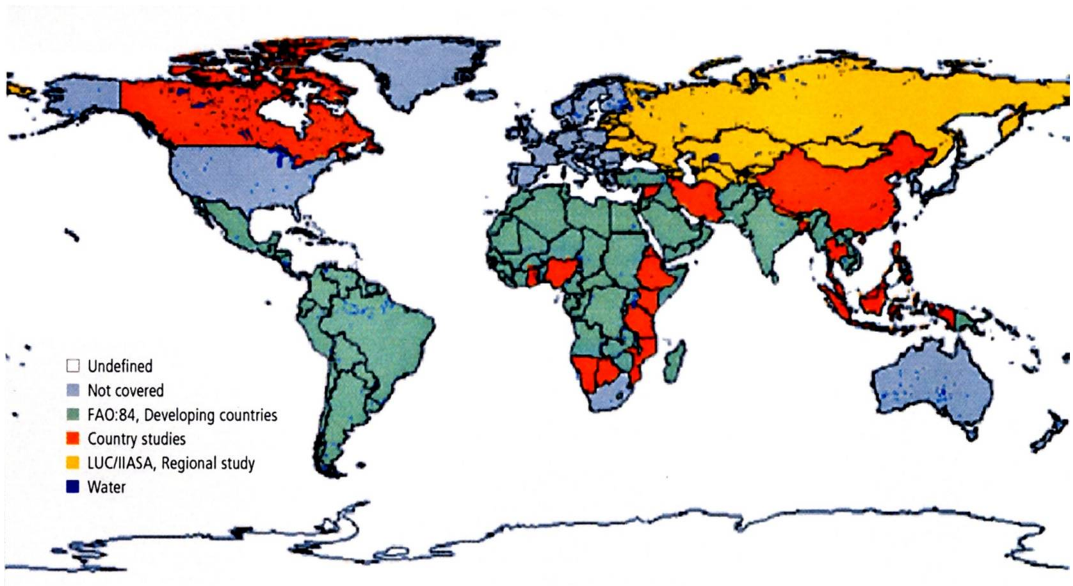

Figure 9. Regional and country studies undertaken to date.

4.2. Limitations of the Approach

Important caveats concerning the Global AEZ results must be considered. While the study is based on the most recent global data compilations, the quality and reliability of these data sets are known to be uneven across regions, including, for example, soil data based on the FAO/UNESCO Soil Map of the World (FAO, 1995). Substantial improvements are being made to the soil information, and several regional updates have recently become available.

The current status of land degradation cannot be inferred from the Soil Map of the World. The only study with global coverage—the GLASOD or Global Assessment of Soil Degradation study (ISRIC/UNEP, 1991)—indicates that the status of land degradation may very well affect potential productivity of land. However, this degradation study offers insufficient detail and quantification for application within the Global AEZ model.

Socioeconomic needs of rapidly increasing and wealthier populations are the main driving forces in allocating land resources to various uses. Such considerations are critical for rational planning of sustainable agricultural development. As an extension of basic land productivity assessments, IIASA and the FAO have introduced interactive multiple-criteria model analysis for use in national and sub-national resource planning. It is at this level of analysis that socioeconomic considerations can be effectively taken into account.

Though various modes have been pursued for ground-truth control and verifying results of the Global AEZ suitability analysis, there is a need for further validation of the results and underlying databases.

Glossary

Agro-ecological zones: Land resources mapping units, defined in terms of climate, landform, soils and land cover, and having a specific range of potentials and constraints for land use.

Agro-ecological zoning: The division of an area of land into smaller units, which have similar characteristics related to land suitability, potential productivity and environmental impact.

Agronomically attainable yields: The maximum yield that can be achieved by a given cultivar in a given area, taking account of climatic, soil and other physical and biological constraints.

Crop environmental requirements: The environmental conditions of land necessary or desirable for the successful growth of a crop.

Growing period: The period during the year when both moisture and temperature conditions are suitable for crop production. (A temperature-related growing period refers to the period during the year when temperature conditions are suitable for crop production).

Land: An area of the earth's surface, the characteristics of which embrace all reasonable stable, or predictably cyclic, attributes of the biosphere vertically above and below this area including those of the atmosphere, the soil and underlying geology, the hydrology, the plant and animal populations, and the results of past and present human activity, to the extent that these activities exert a significant influence on present and future uses of land by man.

Land quality: A complex attribute of land which acts in a manner distinct from the action of other land qualities in its influence on the suitability of land for a specified use.

Land suitability: The fitness of a given type of land for a specified kind of land use.

Land use: The management of land to meet human needs. This includes rural land use and also urban and industrial use.

Land utilization type: A use of land defined in terms of a product, or products, the inputs and operations required to produce these products, and the socio-economic setting in which production is carried out.

Matching: The process of comparing land use requirements with land qualities or land characteristics, to arrive at a land suitability classification.

Multi-criteria analysis: A set of techniques used to solve problems, which involve several objectives being considered simultaneously. In the context of integrated land use planning and management, multiple criteria analysis techniques are applied to analyze various land use scenarios considering simultaneously several objectives such as maximizing revenues from crop and livestock production, minimizing cost of production and environmental damage from erosion.

Population supporting capacity: Assessment of the number of people a given area can support based on the nutritional output of the crop and livestock production.

Sustainability: A measure of whether or not a defined system of land use can be maintained at acceptable levels of productivity or service with realistic levels of input yet without progressive physical, biological, economic, or social damage to the environment on a specific site over a stated period of time.

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Biographical Sketches

Günther Fischer is a senior scientist at the International Institute for Applied Systems Analysis (IIASA), leading a major research project on *Modelling Land Use and Land Cover Changes (LUC),* developing 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 and water use. Since 1980 he has been collaborating with FAO on the development, implementation and application of the AEZ methodology to global, national and regional resource appraisals for decision support.

Mahendra Shah specializes in sustainable development, economic planning, and emergency relief operations. He was special advisor to UNCED and prepared the Earth Summit report "The Global Partnership for Environment and Development - A Guide to Agenda 21". Shah also served as Executive Secretary of the CGIAR system review and co-authored with Maurice Strong, “Food in the 21st century—from Science to Sustainable Agriculture”. Shah joined IIASA as a senior scientist in January 2001 to work on climate change and agricultural vulnerability. He is also the coordinator of IIASA—UN relations.

Harrij van Velthuizen is land resources ecologist and specialist in agro-ecological zoning. He was member of the working group that developed FAO’s agro-ecological zones (AEZ) methodology. With support of FAO he initiated, in 1995, at IIASA the Global AEZ study. In 2001, he joined IIASA’s *Modeling Land Use and Land Cover Changes (LUC)* project, to focus on expanding and enhancing AEZ models and applications.

Freddy Nachtergaele is a Doctor in agronomy who has been working for the Food and Agriculture Organization of the United Nations in Rome as a Technical Officer for Soil Resources and Land Classification with the Land and Water Development Division since 1989. Prior to that he was a land resources expert for FAO in field projects in North and East Africa and in Southeast Asia. He is co-author of the Global Agro-ecological Zones study, vice-Chairman of the IUSS working group on the World Reference Base for Soil Resources, and he coordinates the update of the FAO/UNESCO Soil Map of the World at FAO under the Global SOTER programme. He is the author of numerous scientific articles in the field of agro-ecological zoning, land evaluation, land-use planning and soil classification.

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