# A quickscan of global bio-energy potentials to 2050

An analysis of the regional availability of biomass resources for export in relation to the underlying factors

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## ABSTRACT

There are many scenarios that project a further increase in the demand and use of modern biomass as a renewable (green or $CO_2$ neutral) source of energy (e.g. (Lashof and Tirpak 1990; Hall *et al.* 1993; WEC 1994; Fujino *et al.* 1999; IPCC 2000; Fisher and Schrattenholzer 2001). Estimates of the bioenergy production potential in 2050 vary from 33 to 1135 $EJy^{-1}$ (Hoogwijk 2002).

Concerns arise to what extend the earth is capable of producing an additional supply of biomass without further increasing stresses on the environment or endangering the food supply. The highest potential comes from energy crops produced on degraded land and surplus agricultural land (0 to 998 $EJy^{-1}$). Most existing studies use a top-down approach and exclude information from existing studies on agriculture and forestry. In this study a *bottom-up* analysis of the theoretical global bioenergy production potential is carried out based on the *best available knowledge.* Specific attention is paid to:

- the development of a *methodology* to calculate bioenergy production potentials.
- the impact of *underlying factors* that determine the bioenergy production potential.
- the impact of *sustainability criteria* such as no deforestation, no competition for land between bioenergy production and food production and protection of biodiversity and nature conservation.
- identify gaps and weak spots in the *knowledge base*.

The key elements that determine the bioenergy production potential are identified: population growth, per capita consumption of food, demand for wood, crop yields and the production efficiency in the animal production system (and the potential to increase yields through more intensive management systems), natural forest growth and wood production from plantations. Data and scenarios for these and other factors are taken from a variety of international sources (e.g. FAO, WB, IFPRI, IIASA, RIVM, UNPD, EFI). *Ranges* for the various factors that determine the bioenergy production potential are analysed. An Excel spreadsheet tool was used to analyse the impact of various elements on the global and regional bioenergy production potentials in 2050.

Results indicate that the key factor for bioenergy from specialised bioenergy crops is the type of agricultural management system applied to produce food. If a type of agricultural management is applied similar to the best available technology in the industrialised regions, the world is capable of producing the demand for food projected for 2050 using only a fraction of the present agricultural land. The potential to increase global average crop yields ranges from a factor 2.9 to 3.6 (dependant on the demand for food and feed crops). The potential to increase the production per kilogram feed ranges from a factor 1.1 in the case of chicken meat to a factor 3 for bovine meat. Particularly pastoral (grazing) production systems in the developing countries have a very low production per hectare pasture land. A shift from extensive pastoral production systems to intensive landless production systems (in which all feed comes from feed crops), results in large areas surplus pasture land. In total, between 0.7 Gha to 3.6 Gha agricultural land can be made available for bioenergy production in 2050 (dependant on the demand for pasture land and the demand for food and feed crops), equal to 14% and 70% of the present total agricultural land use. The total bioenergy production from these surplus areas ranges between 215 to 1272 $EJy^{-1}$. Other potential sources for bioenergy are agricultural residues (58 to 72 $EJy^{-1}$ in 2050, dependant on the production of crops) and surplus forest growth (0 to 37 $EJy^{-1}$ in 2050, dependant on the assumptions on forest areas available for wood supply and the rates of plantation establishment).

The regions with the highest potentials for bioenergy production are sub-Saharan Africa (0.1 to 0.7 Gha surplus land, equal to 31 to 317 $EJy^{-1}$ bioenergy in 2050) and the Caribbean

& Latin America (0.2 to 0.6 Gha or 47 to 221 $EJy^{-1}$ in 2050). The potential from these regions comes from the large areas suitable cropland, large areas pasture land presently used and the present low productive and inefficient production systems. The other developing regions, South Asia and the Near East & North Africa are typical land stressed regions, which will increasingly depend on food imports. The potential in these regions is limited to areas not suitable for food production, but suitable for bioenergy (this also partially goes for East Asia).

North America and Oceania have considerable potentials to produce bioenergy on surplus agricultural areas (0.1 to 0.3 Gha equal to 20 to 174 $EJy^{-1}$ in North America and 0.2 to 0.4 Gha equal to 38 to 102 $EJy^{-1}$ for Oceania). The bulk of this potential comes from pasture land, indicating the large areas presently used that can be made available if industrialised production system are used. The land balance for West Europe is less favourable, however, projections indicate a limited change in consumption and population and further increases in production efficiency may further optimize agricultural land use patterns and management. The potential of West Europe is estimated at 12 to 64 Mha or 5 to 30 $EJy^{-1}$ bioenergy in 2050.

The most robust potentials can be found in the former transition economies. Since the end of the Soviet period and the subsequent economic reforms, consumption, production and productivity decreased dramatically. It will taken several decades before consumption levels are back to their old levels. If agricultural productivity in these regions can be optimised, between 0.1 to 0.5 Gha land can be made available for bioenergy in the C.I.S & Baltic States, equal to 45 to 199 $EJy^{-1}$. East Europe has a potential of 4 to 40 Mha, equal to 3 to 26 EJy-1.

We acknowledge that there are many uncertainties related to the data and scenarios included in this study. Further research and more reliable and detailed data are required to allow assessments of the (regional) implementation potential and to make more accurate bioenergy potential assessments. Key priorities for future research are:

- The dynamics on the socio-economic system determines land use patterns and yields. In reality, yields are the result of many complex iterative interactions between included in the entire socio-economic system (e.g. prices of land and labour, available infrastructure, trade negotiations, interest rates, education level of agricultural workforce). These complex interactions are poorly understood and are very difficult the quantify.
- The extend and severity of environmental degradation and the impact of various management systems. Despite widespread public and political attention for the link between agriculture and various forms of environmental degradation, such as fresh water depletion, soil degradation (salinisation, soil depletion, desertification, loss of topsoil) and loss of biodiversity, there are considerable uncertainties in the perception of the seriousness of these issues and the consequences for agriculture.

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# 1. INTRODUCTION

Biomass is receiving more and more attention as a source of energy. Biomass has the potential to provide a renewable (green or $CO_2$ neutral) energy source, locally and readily available in large parts of the world. In its traditional form biomass (e.g. fuelwood, manure) accounts for 38+/-10Ejy$^{-1}$, modern biomass (e.g. use of biomass for electricity or fuel generation), from now on also referred to as bioenergy, contributes ca. 7 EJy$^{-1}$ (Turkenburg 2000). For comparison: the global primary energy consumption in 2001 is 420 EJ (IEA 2003).

There are many scenarios that project a further increase in the demand and use of modern biomass (e.g.). Estimates of the bioenergy production potential vary from 33 to 1135 EJy$^{-1}$ (Hoogwijk 2002). The major reason for the differences is that the two most crucial factors, land availability and yields, are very uncertain (Berndes 2003). This uncertainty results from the fact that most studies are either demand or resource focussed and demand and supply interactions are poorly understood and difficult to model (Döös and Shaw 1999). For a detailed analysis and comparison on 17 studies on global biomass production potentials see Berndes *et al.* (2003).

As with most agricultural commodities, there are regions where there is a demand for bioenergy, but due to economic factors (too expensive) or physical limitations (lack of natural resources) domestic production can be unattractive. There will also be regions with an opposite demand-supply situation. Consequently, if the scenarios that project an increasing use of modern biomass becomes reality, large scale production and trade of biomass (biotrade) can become reality. The transportation of biomass comes with economic and environmental costs, but research has shown that e.g. biomass from South America imported to the Netherlands is economically attractive and that the total energy losses from production to delivery within the Netherlands is limited to 15% of the primary energy in case of pellets (Hamelinck *et al.* 2003). Already at this moment, the Netherlands, Denmark and Sweden import (small amounts of) biomass for electricity generation (Hamelinck *et al.* 2003; Ericsson and Nilsson 2004) since domestically produced biomass is more expensive.

Taking into account the projected growth of population, income and consequently demand for food and biomaterials, concerns arise to what extend the earth is capable of producing an additional supply of biomass without further increasing stresses on the environment or endangering food supply. Bioenergy in general will only be accepted if the electricity is not only 'green', but also sustainable with respect to other indicators such as the impact on food security and deforestation.

In previous studies on biomass resources, a wide variety of approaches and methodologies is used to estimate bioenergy potentials. The state-of-the-art in this field of research consists of:

- studies that use integrated models such as the Global Land Use and Energy Model (GLUE) (Fujino *et al.* 1999), the Integrated Model to Assess the Global Environment (IMAGE) (Leemans *et al.* 1996) and (Berndes 2003) , IIASA's Basic Linked System Model of the world food system (BLS) (Fisher and Schrattenholzer 2001)
- studies that estimate ranges in the contribution of biomass in the future global energy supply by reviewing previous assessments e.g. (Lysen 2000; Hoogwijk 2002; Berndes 2003).

Many more studies have been carried out since the first publications on biomass resources appeared early 90's. Most of these studies are either demand driven (focussing on the demand for bioenergy) or supply driven (focussing on the sources of bioenergy) and use a top-down approach. Secondly, most studies pay limited attention to the quality of the data used, methodological uncertainties, the impact of the various factors that determine the bioenergy production potentials and exclude data from existing agricultural and forestry outlook studies.

In this study a bioenergy potential assessment is carried out:

- based on a extensive review/assessment of existing databases, scenarios and studies.
- with specific attention for the impact of the most important factors that determine the biomass production potential, such as population growth, consumption patterns, crop yields and the applied level of (agricultural) technology. Different scenarios are composed for these factors based on the best available information from various international studies (e.g. FAO, UN, IFPRI) as well as our own assumptions. In addition, the potential impact of sustainability issues such as deforestation, nature conservation, protection of biodiversity and competition for land between e.g. bioenergy production and food production on the bioenergy production potentials are analysed. The results show which regions are (un)likely to have a biomass surplus and under which conditions and scenarios a surplus is feasible.
- with specific attention for the identification of gaps and weak spots in the knowledge base concerning these issues.
- bottom-up to the year 2050.
- using a methodology also applicable at the national level.

The calculated biomass production potentials are compared to the domestic energy demand in 2050 in each region to provide a measure for the biomass exporting potential of a region. The data presented in this report are meant to provide scientific input for shaping perceptions on future of bioenergy production and discussion on the issue if and under which conditions the production, use and trade of bioenergy is a realistic and sustainable option. Based on the assessment made in this report, some promising regions will be selected for further in-depth analysis. This is done in a follow-up study within the Fair Biotrade project.

This report consists of six sections and Appendixes A to T. In section 2 the approach and methodology is described. In section 3 results and data for different factors and indicators included in this study are presented. Section 4 gives an overview of the results, which are further discussed in section 5 (sensitivity analysis) and 6 (discussion and conclusion). The Appendixes contain intermediate results, details of the calculation procedures and additional information on various issues.

# 2. METHODOLOGY AND APPROACH

This section gives a brief overview of the approach (2.1) and methodology (2.2) used in this study. The details of the methodology such as data sources, scenarios, formulas, etc. are given in section 3.

## 2.1 APPROACH

Four types of biomass are included in this study that represent the most important sources of bioenergy: biomass from specialized energy crops, agricultural residues, residues from the wood processing industry and biomass subtracted from forests, manure and organic (urban) waste. Due to a lack of data and literature on the potential of aquatic biomass such as algae, seaweed and marine micro flora, this category was excluded.

Previous studies indicate that the highest potential comes from specialised bioenergy crops produced on degraded land and surplus agricultural land (e.g. (Lashof and Tirpak 1990; Hall *et al.* 1993; Sorensen 1999; Fisher and Schrattenholzer 2001). The range in estimates is however very large (0-988 $EJy^{-1}$). Therefore, the core focus of this study is on assessing the development of land use patterns and how these could be influenced.

In this study a *bottom-up* analysis of the bioenergy production potential is carried out based on the *best available knowledge* on the different factors that determine the bioenergy production potential. Based on a large number of bioenergy potential assessments, studies on the present state and future of agricultural or forestry and reviews of these studies, the key elements that determine the bioenergy production potential are identified. The elements are combined in a spreadsheet model used to estimate regional bioenergy production potentials with databases on:

- population growth
- per capita food consumption and composition
- land use patterns
- crop yields (food crops and bioenergy crops)
- efficiency of the animal production system
- feed inputs in the animal production system
- wood consumption and production (fuelwood and industrial roundwood)
- natural forest growth

Specific attention is given to the quality of data, gaps in the knowledge base, ranges of projections and uncertainties in existing outlook studies and the impact of various sustainability criteria for the production and trade of bioenergy such as avoidance of deforestation and competition between food production and bioenergy production.

By using best available data from various studies and statistics, we aim for:

- a better understanding of the impact of different factors that determine the bioenergy potential and
- a more detailed insight in the state of knowledge in different research areas (economics, demographics) and the impact of these uncertainties on the different factors that determine the bioenergy potential. In doing so, the needs for additional and/or better data is made explicit.

Note that the term 'potential' in this report refers to three types of potential ($EJy^{-1}$) defined as follows (adjusted from (WEC 1994):

- *theoretical potential*: the theoretical maximum potential is limited by factors such as the physical or biological barriers that can not be altered given the current state of science. E.g. the theoretical potential yield of a crop is the yield that is limited by the

efficiency of photosynthesis, other yield limiting factors can be compensated through technology.
- *technical potential*: the potential that is limited by the technology used and the natural circumstances. E.g. the yield of a crop based a certain level of technology. The technical potential is the same as the theoretical potential if the technologies used that do not limit productivity.
- *economic potential:* the technical potential that can be produced at economically profitable levels, depicted by a cost-supply curve of secondary biomass energy.
- *implementation potential*: the maximum amount of the economic potential that can be implemented within a certain timeframe, taking (institutional and social) constraints and incentives into account.

For various reasons described below, the focus in this study is on the *technological potential*.

## 2.2 OVERVIEW OF THE METHODOLOGY

Figure 1 gives an overview of the key elements included in our analysis and the most important correlations between them as included in this study.

The focus of this study is mainly on specialised bioenergy crops (section 2.2.1), (surplus) wood growth from forests (section 2.2.2) and agricultural and forestry residues (section 2.2.3). Data on the potential of manure and (organic) urban waste are derived from literature. The various elements shown in figure 1 are analysed separately, meaning that no demand supply matching in economic terms is included. In reality, the bioenergy production potential is influenced by numerous more underlying and interacting variables, but due to a lack of data, time and resources, our qualitative analysis is restricted to the elements in figure 1. Various other relevant factors that for various reasons could not be included in the analysis outlined in figure 1, are included in the discussion and the description of different elements.

### 2.2.1 Specialised bioenergy crops

The production of bioenergy requires land. In our opinion, the production of bioenergy from specialised bioenergy crops must be regarded as unsustainable if one or both of the following criteria is not met[1]:
- the production of bioenergy is only allowed on *abandoned or surplus agricultural land* (bioenergy production is not allowed to compete with agricultural land use for food production). Surplus agricultural land includes both areas degraded land no longer suitable for commercial crop production and areas that are taken out of production due to a surplus of productive area.
- deforestation due to the demand for suitable cropland for bioenergy production is not allowed.

The latest projection by the Food Agricultural Organisation (FAO) to 2030 (FAO 2003b) indicate a significant increase in agricultural land use in the developing countries; agricultural land use in the transition and industrialised regions is expected to increase marginally, if not remain stable or decrease. However, the projected changes come with considerable uncertainty. The functioning of the entire socio-economic system that determines land use patterns is poorly understood and very difficult to capture in a model

[1] Obviously, many more sustainability criteria are thinkable for the production, processing and trade of bioenergy (although much depends on one's personal perception on what is sustainable or not). Various efforts are presently under way to identify relevant indicators and certification systems and analyse their impact on the bioenergy potentials based on existing criteria and develop, similar to e.g. the Forest Steward Council (FSC) certification system for wood products (e.g. (Lewandowski and Faaij 2004).

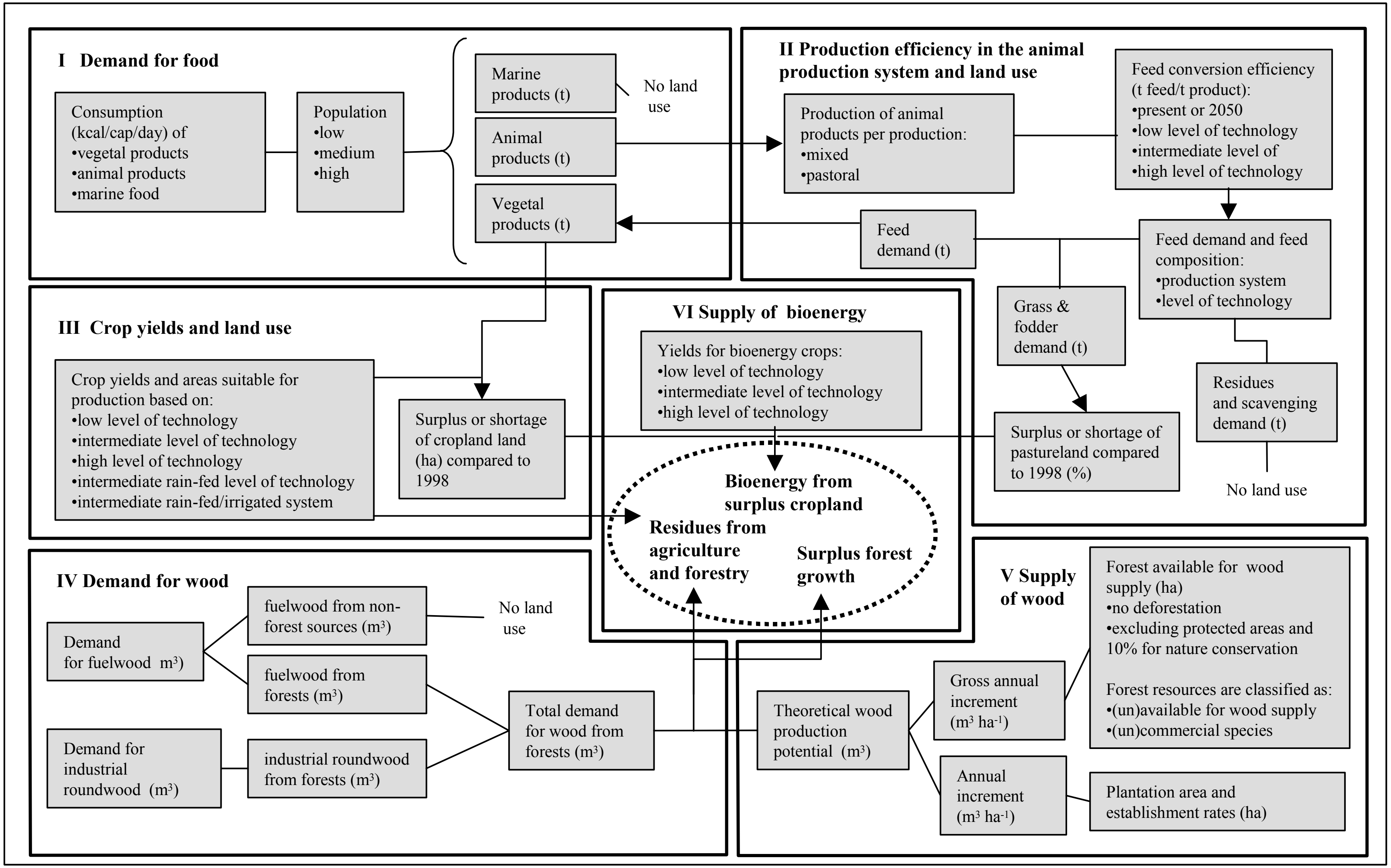


*Figure 1.* Overview of the key elements in the assessment of the bioenergy potential from specialised bioenergy crops.

and to predict (especially considering the long time frame included and potentially large impact of bioenergy production on the agricultural production system and land use). This uncertainty especially relates to the supply side (future land use pattern, development of technologies, sustainability of production systems and yields), more than the demand side (demand for food and biomaterials). On the supply side, many studies indicate that there are still large 'exploitable yield gaps' between regions and countries that could be closed (at least in theory; e.g. (Duwayri *et al.* 1999). This (technical) potential seems large enough to increase yields well above levels projected by the FAO for 2030, in especially the developing regions. The closing of these gaps is a matter agricultural *management*[2]. Existing projections of the future of agriculture usually exclude an additional demand for agricultural products (bioenergy) and complementary (unforeseen) changes in agricultural policies. Therefore, the focus of this study is on the *technical potential* to increase yields, reduce the area under (food)crop production and make land available for bioenergy production.

**I Demand for food**

The consumption of animal products and food crops is the per capita consumption multiplied by the population size. Projections of the per capita consumption of vegetal production and animal products to 2050 are based on various existing projections, trend extrapolations and our own guestimates (section 3.1).

**II Production efficiency in the animal production system and land use**

The demand for animal products is translated into land use based on three variables:

- the production system (pastoral, landless or a combination of the two referred to as 'mixed'). Pastoral (grazing) production system is usually more land intensive and requires more biomass than a landless production system in which all feed comes from feed crops.
- the feed conversion efficiency. The feed conversion efficiency is defined in this report as the total demand of biomass (dry weight) per kg animal product[3]. Data on feed conversion efficiency are dependant on the production system and the level of technology applied.
- the feed composition. A wide variety of products is used as feed in the animal production system. In this study they are classified as: grasses & fodder, feed from crops and residues & scavenging. The feed composition is dependant on the product system and level of technology.

Based on the three variables described above, the demand for various types of animal feed can be calculated. The demand for residues and scavenging is included in the calculations of the bioenergy potential of agricultural residues. The demand for crops used for feed is further included in the calculations of the land use for crop production. An increase in demand for pasture biomass requires an increase of the productivity of permanent pastures or indicates an increasing grazing intensity. A decreasing demand for pasture biomass indicates a similar decrease in the areas permanent pastures.

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2 The term *management* usually refers to the issues as the use of fertilizers, pesticides, mechanised tools, improved breeds, double cropping, the application of irrigation. In this study the term also includes optimalisation of land use patterns to minimize land use or optimize profits. The terms *production system* and *level of technology* are the same as *management*, except that land use optimalisation is not included. The terms *production system* and *level of technology* are used interchangeable in this report.

3 In literature, the feed conversion efficiency is often defined as the ratio dry weight biomass input to fresh weight production of animal product (input/input). A high feed conversion efficiency indicates in reality a low efficiency of land use. To avoid confusion, this report uses a the ratio fresh weight production of animal product to dry weight biomass as input (output/input).

**III Crop yields and land use**

The demand for crops is translated into land use, using an Excel spreadsheet tool. In this spreadsheet, the demand for crops can be allocated to areas with the most favourable agroclimatological conditions for crop production and thus the highest yields, thereby minimizing agricultural land use. If these very suitable areas are fully occupied, the remaining demand is allocated to suitable areas, followed by moderately suitable areas etc. Alternatively, the most productive areas can also be allocated to other land use categories e.g. for bioenergy production, leaving the less productive areas for food production. The areas (and yields) very suitable, suitable, moderately suitable etc. are determined by:

- the natural circumstances such as radiation, rainfall, soil texture etc.
- the level of technology applied. The term level of technology refers to the use of mechanised tools, optimized varieties with higher harvest indexes, irrigation, fertilizers, pesticides etc.
- the use of these areas for forests, plantation areas, urban areas, crops not included in the model etc. Various simple allocation rules are used to determine the extends of very suitable, suitable etc. areas to these categories.

Data from a crop growth model are used that include both the effect of natural circumstances and the level of technology used (the same goes for the yields of the bioenergy crops). The import and export of crops and animal products is considered constant at the (absolute) level of 1998. Any increases in food consumption have to produced within that region. If however, the area cropland in a region and/or the yields per hectare that is determined by the applied level of technology are insufficient to meet the projected demand for food in that region, the remaining demand for food is allocated to regions with a surplus of suitable cropland.

The resulting bioenergy production is the area surplus cropland and permanent pasture multiplied by the yields of woody bioenergy crops specific for the suitability of these areas.

### 2.2.2 Residues

The term residues refers to a wide variety of types of biomass: included are crop harvest residues (e.g. straw, stalk, leaves), crop processing residues (oilcakes, hulls, shells), residues from the livestock sector (dung), forestry harvest residues (twigs, branches, stumps, uncommercial logs), forestry processing residues (sawdust, chips) and wastes (food that has become unsuitable for consumption due to decay). The calculation of the technical bioenergy potential from residues is rather straightforward: the quantities wood or food that are harvested, processed or used are multiplied by the harvesting-, processing- or waste generation coefficients (section 3.9). These coefficients are determined by the efficiency of the technology used. The technical potential of residues for bioenergy is further limited by:

- alternative uses as animal feed, animal bedding, tradition fuel or for material production (paper or fibreboard). The use of residues for feed is calculated as described in section 3.4.
- ecological requirements. Residues are sometimes deliberately left on the field to prevent soil erosion or to maintain or improve the structure and fertility of the top soil.
- the amount of residues that realistically can be collected.

### 2.2.3 Surplus forest growth

A large number of studies is used to analyse the global demand for fuelwood and industrial roundwood in 2050. The range found in literature is translated into three scenarios. The supply of wood consists of:

- trees outside the forest (e.g. orchards, roadside vegetation)
- natural forest growth (based on data on area forest multiplied by the annual forest growth (gross annual increment, (GAI). 10% of the forest area is set aside for biodiversity protection and nature conservation
- production from (non) industrial plantations.

The demand for wood is compared with the supply of wood to estimate a theoretical gap or surplus in wood supplies. In reality, demand supply interactions automatically lead to a new equilibrium, but due to the complexity of this aspect it is not included in this study.

# 3. REVIEW AND SELECTION OF DATA AND LITERATURE

This section gives a detailed overview of the datasets, formulas and projections used to estimate the regional bioenergy production potentials in 2050.

Most data used in this study were available at a country level, such as per capita consumption, population and land use. Other data were only available at a much lower geographical resolution, e.g. per continent, global average or estimates for a few countries. Further, many data comes with a considerable uncertainties, as further analysed in the relevant sections. To avoid suggesting a too high accuracy of the results and to keep the amount of data presented manageable, the results are aggregated and shown for 11 regions (Appendix A). The methodology can however be deployed at a more detailed level as shown in section 6.

The base year of this study is 1998, for which many data were available from the databases from the Food Agricultural Organisation (FAO STAT, (FAO 2002a). Data derived from various other sources were not always available for 1998, so data from other years were also used. Considering the overall uncertainty related to many data and year-to-year variation in data, the base year is perhaps best defined as 'by the end of 90's'.

Issues included are the demand for crops (section 3.1), the demand for wood (section 3.2), historic and future land use for crop production (section 3.3), land use for the production of animal products (section 3.4), land use for wood production (section 3.5), build-up land (section 3.6), the land use allocation model included in the Excel spreadsheet tool (section 3.7), bioenergy yields (section 3.8) and the production of agricultural and forestry residues (section 3.9).

## 3.1 DEMAND FOR CROPS AND ANIMAL PRODUCTS

The demand for animal products or crops is based on the classification applied in the Food Balance Sheets of the FAOSTAT database (FAO 2002a), see the section below.

*Input*

The demand for animal products or crops of type (c) in a certain region (r) is calculated based on the formula below. For each of these factors scenarios are included based on various sources in combination with our own calculations and assumptions as described in sections 3.1, 3.3, 3.4 and Appendix B, C, E and I.

$Demand_{cr} = (Food_{cr}. + Proc_{cr} + Other_{cr}) \times Pop_r + Feed_{cr} + Waste_{cr} + Seed_{cr} – Export_{cr} + Import_{cr}$

- $Food_{cr}$ = per capita food consumption. The projected consumption of food per capita to 2030 is based on FAO projections (FAO 2003b). Small differences between our projections and the FAO projections due to differences in classification and differences in base year data. Trend extrapolation in combination with data from other sources are used to extrapolate projections to 2050 and to compose low and high scenarios. See further section 3.1.2.
- $Proc_{cr}$ and $Other_{cr}$ = the per capita consumption of processed food and the use for other purposes. The latter includes the manufacture for non-food purposes, e.g. oil for soap and statistical discrepancies. The per capita consumption of processed food and the per capita use for other purposes is assumed to increase at the same speed as the per capita food consumption. See further section 3.1.2.

- $Pop_r$ = population. Population scenarios to 2050 are based on the latest projections from the United Nations Populations Division (UNPD 2003). Included are the low, medium and high variant. See further section 3.1.1.
- $Feed_{cr}$ = feed. The total demand for feed is taken from the calculations of the animal production system (figure 1, section 3.4 and Appendix I).
- $Waste_{cr}$ = wastes. Data on the present percentages of the total supply that are wasted are used to estimate waste ratios common in inefficient production systems and waste ratios common in efficient production systems. Data on waste percentages in different regions are shown in Appendix L.
- $Seed_{cr}$ = seed. Data on the present ratio seed use to total supply are calculated based on data from the FAO STAT database. The results show that these ratios vary little compared to the factors in the equation. The seed use ratios are assumed constant in this study.
- $Export_{cr}$ and $Import_{cr}$ = export and import. The import and export of food crops and animal products is kept constant at the (absolute) level of 1998, unless the projected demand for food and feed of a region can not be produced within that region, see further section 3.3 and 3.4).

### 3.1.1. Population growth

Population growth is the most important cause of increased demand for food: in the period 1967 to 1997 the total demand for agricultural crops and livestock products increased by 2,2 % per year of which 1.7 % due to population growth. In the following thirty years these percentages are expected to be 1,5 and 1,0 % respectively (FAO 2000a). It can be stated that the accuracy with which food demand (and thus also biomass supplies) can be predicted is primarily dependant of the reliability of projections of the growth rate of the population (Doos and Shaw 1999).

*Input*

Historic data and scenarios for the growth of population are taken from the (online) database of the United Nations Populations Division, 2003 version (UNPD 2002). More than 99% of the world's population is included in this study. The UNPD scenarios are the most widely used source for population scenarios. This does not mean that these projections are free of error. A comparison of past UNPD projections with actual data shows that population projection errors[4] are average 4% (global population) with a range of +0.5% to 7.1%. Regional projections errors were between –35,4% to +30,8%, but generally below 10% (IFPRI 2001b). The latest projection indicates a total world population of 8.9 billion in 2050, 1,1 billion less than projected in 1990 (partially because the AIDS epidemic is more severe than expected). For a further discussion of population projections, see Appendix E.

*Calculations*

The UNPD data include several scenarios of which three are included in this study. Data are given per country and summed up to compose regional totals. The medium growth scenario is the most likely scenario, the high and low scenarios represent the upper and lower limit within population in expected to develop. Therefore, the medium population growth scenario is

[4] Projection error = 100 (projected level–actual level)/actual level. A positive value is an overestimate, a negative an underestimate.

frequently used for outlook studies[5]. The FAO used the 2000 revision in the WATO 2015-2030 report (FAO 2003b). The IFPRI used the 1999 revision of the UNPD projections (IFPRI 2001a).

*Output*

The projected population growth in the medium scenario is shown in figure 2.

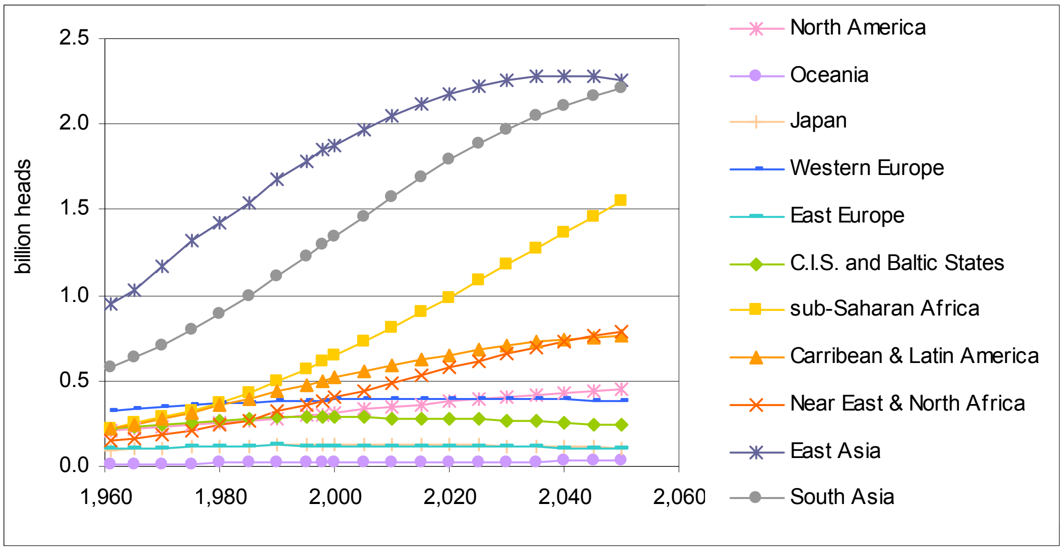


*Figure 2.* Medium population growth scenario 1960-2050 (1000 heads). Source: (UNPD 2003)

### 3.1.2. Per capita consumption of food and wood

Changes in the per capita consumption of food and wood is the second most important factor that determines the future demand for food and wood. The driver behind increasing the per capita consumption is income, but several methodological problems make it difficult to calculate consumption scenarios based on mathematical correlations between GDP and consumption and GDP projections. These problems relate mainly to the calculation and use of GDP – consumption elasticities. Elasticities are difficult to calculate, because elasticities are derived from historic time series for GDP and consumption, which are in turn influenced by variations in prices due to natural circumstances, (agricultural) policy and continued increasing production efficiency. The prices of cereals decreased by some 75% during the last decades, but this strong decrease in prices is expected to level of, due to a slowdown of increases in yields and continued increase in demand.

Ideally, the impact of increasing yields and production efficiency is excluded when calculating the correlation between GDP and consumption. Alternatively, a comprehensive model can be used in which these factors are incorporated. Even if elasticities were available that accurately describe the correlation between GDP and consumption, the chosen timeframe of 50 years limits the use of the calculated elasticities, because elasticities vary over time due to saturation effects or changing cultural preferences. The use of historical growth rates and correlations often lead to absurd results. Even if this problem was solved, the consumption projections strongly depend on

[5] The IPCC SRES scenarios are also a frequently used source of population projections (IPCC, 2000). These scenarios are based on storylines and should not be used separately from the other factors discussed in the storylines, these are not further discussed.

the chosen GDP scenario. Unfortunately, GDP scenarios also come with considerable uncertainty. Please note that comprehensive demand and supply modelling is possible, as shown by e.g. the IFPRI projections to 2020 (IFPRI 2001a), but such an exercise is considered too complex for this study and the frame (to 2050). Instead, we used the per capita consumption scenarios and info on saturation levels from existing studies as a starting point. More details on the methodological issues mentioned above and other are described in Appendix D.

*Input*

Base year data are derived from the FAOSTAT database (FAO 2003b). The increase in per capita consumption is derived from existing studies, mainly FAO (FAO 2003b), supplemented by (IFPRI 2001c) and (IMAGE-team 2001). A more detailed description of historic trends in food consumption and other data included is given in Appendix B.

*Calculations*

The future demand for crops is based on the *relative* increase in kilocalories (kcal) projected by the FAO to 2015 and 2030 (FAO 2003b). The relative increase for different crop types or types of animal product are aggregated into 9 product groups (cereals, roots & tubers, sugar crops, pulses, oilcrops, vegetables, stimulants, spices and alcoholic beverages). The relative increase per product group is multiplied by the base year consumption data per product group to calculate the future consumption per crop type of type of animal product. Data on the consumption of fish are not included in the FAO Supply Utilisation Accounts (SUA) received from the FAO that provide detailed data on future consumption levels. Data on the future consumption of aquatic products were derived from FAO projections to 2030 (FAO 2003b). Due to differences in base year data and definitions between the FAO projections and the calculations in this study, the relative increase in consumption was upscaled or downscaled to match the total daily per capita consumption in kcal projected by the FAO, supplemented by data from other studies (IFPRI 2001a; IMAGE-team 2001). Trend extrapolation was used to compose the consumption scenarios to 2050. Results of the trend extrapolation were down- or upscaled based on data from the other sources (IFPRI 2001a; IMAGE-team 2001).

We use the FAO projections to 2030 as primary source, because the FAO projections are frequently cited in literature, based on detailed research and are from knowledgeable source. This does not mean that the FAO projections are free of error or that the conclusions are undebated. Projections done in 60's and 70's consequently underestimated consumption, global projection error is larger than 10%, regional projection errors of –20 to –30% are no exception (IFPRI 2001b) Appendix P). Projections (in general) become more uncertain with increasing time horizon so the uncertainty is particularly relevant for the period 2030 to 2050. The high scenario is based on an additional increase in consumption of 50% compared to the projected increase between 2030 and 2050 (=100%). The low scenario is based on 50% of the growth between 2030 and 2050. The process of composing the three scenarios is described in detail in Appendix C.

In all cases however, the projected consumption levels are not allowed to go above 3700 kcal $cap^{-1}$ $day^{-1}$, of which maximum 1100 kcal $cap^{-1}$ $day^{-1}$ animal products (including fish and seafood). This level is taken as the 'preferred level of consumption'. In the industrialised countries, consumption is stabilizing at these levels. Note that since these figures are regional averages, so higher consumption levels are possible.

*Output*

Figure 4 shows converging trends in the percentage of daily kcal intake from animal products indicating the levelling off of consumption in the industrialised countries and increasing consumption in other countries. The percentage of kcalorie (kcal) intake from animal products has decreased steadily in the regions with the highest consumption of animal products (Oceania and North America) during the last decades (figure 4). The saturation level of animal products is set at 1050 kcal $cap^{-1}$ $day^{-1}$ (the 2001 average of the EU countries in 2001; excluding fish and seafood), equal to ca. 89 kg meat per capita per year and 235 kg milk per capita per year. An additional 50 kcal $capita^{-1}$ $day^{-1}$ is allowed from fish and seafood. Once saturation levels are reached only the substitution of meat by fish is allowed (as is currently occurring in the industrialised regions). The resulting kcal intake per capita is shown in figure 3. Note that the projected average consumption levels in 2030 in all developing regions are well above the 1760 to 1980 kcal $capita^{-1}$ $day^{-1}$ required to avoid under nourishment (based on light activity and population structure in 2030). However, this figure is an average. According to the FAO projections on which these projections are based, the total number of undernourished people is projected to decrease from 815 million in 1990/92 to 440 million in 2030, close to the target set by the World Food Summit of halving the number undernourished in from 1990/92 to 2015. The relative incidence of under nourishment in the developing countries is likely going to decline from 17 to 6% in 2030.

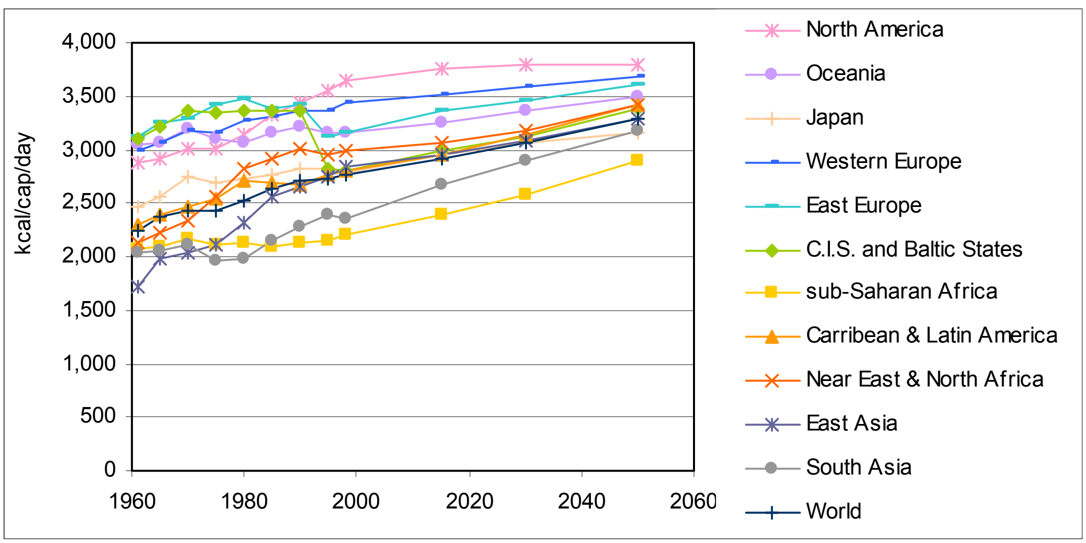


*Figure 3.* Historic and projected per capita total food intake 1961-2050 (kcal $cap^{-1}day^{-1}$). Sources: (IFPRI 2001a; IMAGE-team 2001; FAO 2002a, 2003b), own calculations.

The largest part of the increase comes from vegetal products (+76%), the remaining comes from animal products and seafood. In relative terms however, the consumption of animal products increases much faster than the consumption of vegetal products (+120% and +70% respectively).

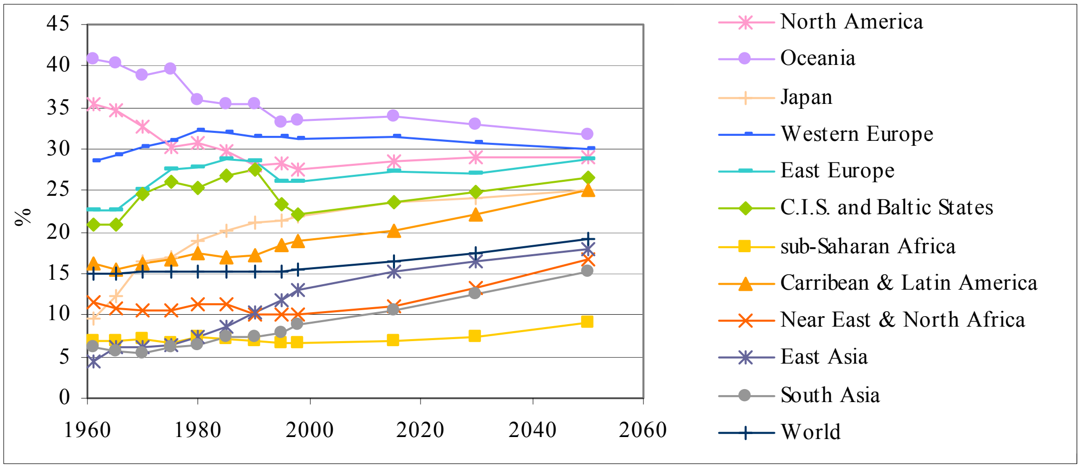


*Figure 4.* Consumption of animal products 1961-2050 (% of total daily caloric intake). Sources: (IFPRI 2001a; IMAGE-team 2001; FAO 2002a, 2003b), own calculations.

Figure 4 shows that the consumption of animal products in many of the developing countries remains well below saturation levels. Consumption in these regions is very responsive to further increases in income or decreases in food prices compared to the scenario underlying the projections included in this study. A small changes in GDP or prices, may significantly further increase consumption in these regions. Consumption in regions with consumption levels near the saturation level are likely less sensitive to changes in prices and GDP. This also means that the projected increase in consumption is more uncertain for countries with low levels of consumption. Further, the projected increases in per capita consumption follow smooth lines. In reality, due to factors generally not included in long-term models such as political changes (and agricultural policies), wars, natural circumstances (droughts, floods) and economic setbacks consumption trends show significant year-to-year changes and effects may last several decades. Such effects are blurred by the aggregation to world regions, but are still visible in the historic data shown in figure 3 and 4 for e.g. the C.I.S. and Baltic States where since the collapse of communism economic restructuring caused a strong decrease in GDP, agricultural subsidies and consumption. It will take several decades before consumption levels have reached their old levels.

## 3.2 The demand for wood

The demand for industrial roundwood is analysed in section 3.2.1 and the demand for fuelwood is analysed in section 3.2.2.

### 3.2.1 Demand for industrial roundwood

*Input*

During the 90's several outlook studies and reviews have been published in which the future consumption of industrial roundwood was estimated. The projections found in literature vary widely, between 1,9 and 3,1 billion $m^3$ in 2050[6][7] (see Appendix F). In general, wood demand and

[6] An exception is the IMAGE A1scenario (high economic growth, which indicates a consumption of 5,1 billion $m^3$ industrial roundwood. This scenario is not further included because the projected consumption levels are much higher than any of the other projections.

[7] According to one of the most recent projections of the FAO, the industrial roundwood consumption in 2030 is 2,4 billion in 2030; trend extrapolation to 2050 yields a consumption of 3,2 billion $m^3$ in 2050.

supply forecasting are less well developed and less understood than for agriculture. Only a few projections dare to go beyond 2010 and those who do, only give data for total consumption of roundwood. Besides this, the data are limited to a subdivision of developed and developing countries. The projections are difficult to compare due to a lack of information on the key assumptions, methodologies applied and not all studies are intended to produce equivalent results (Brooks *et al.* 1996).

*Calculations*

Given the large range in projections, no most-likely scenario was included. The upper range of projections of consumption of industrial roundwood is used as a high scenario, the low range of projections as a low scenario (the consumption of industrial roundwood consumption was 1.6 billion $m^3$ in 2000). The medium scenario is the average of the low and high scenario.

The only study that provides detailed country and product specific data is the Global Forests Product Model (GFPM) of the FAO. Data on consumption of industrial roundwood and fuelwood for the year 2030 were obtained from the FAO. This dataset was used to allocate the three scenarios described above to regional and product specific consumption of industrial roundwood, sawnwood, wood based panels, pulp for paper and paper and paperboard (FAO 1998b).

*Output*

The three scenarios included are:

- The low scenario: 1,9 billion $m^3$ in 2050. This figure indicates the level of consumption indicated by the lower range of projections.
- The high scenario: 3,1 billion $m^3$ industrial roundwood consumption. This represents the highest estimates of industrial roundwood consumption in 2050 (e.g. (Solberg 1996; FAO 2000c).
- The medium scenario: the average of the high and low scenario, equal to 2,5 billion $m^3$.

Despite the projected increase in GDP in all regions, the wood consumption per capita decreases in some regions. This is the combined result of:

- Increasing prices that offset the effect of increased GDP.
- The effects of substitution, recycling and efficiency improvements are responsible for decreasing the demand for forest products and limiting the demand for declining forest products (Sohngen 1997).
- Uncertainties inherent to long term consumption projections.

It is not known to which extend the three scenarios include the effects of technological improvements. Recent studies indicate that both through increasing conversion efficiencies and the development of new wood products which make more efficient use of resources (e.g. medium density fibre board), the growth of demand for industrial roundwood slows down (FAO 2003b). See Appendix F for details on the wood conversion efficiencies.

### 3.2.2 Demand for fuelwood

*Input*

Roughly half of the world's wood consumption (3,3 billion cubic meters) is used as fuelwood (FAO 2002a). Despite the obvious importance of fuelwood, data on the use of fuelwood are largely based on estimates. They are very uncertain and may provide too little information to produce reliable forecasts (EFI 1996). Sharma and others suggest that current consumption is considerably higher than reported by the FAO (Sharma 1992). Nilsson (1996) reports that much fuelwood consumption goes unreported because it never enters the market and consumption data are therefore underestimated.

Increasing income and urbanisation encourage a switch from fuelwood to more modern commercial fuels (gas, oil). On the other hand, rapid population growth in many developing regions and increasing (but still low) income levels of the majority of the fuelwood consumers in mainly rural areas counteract this effect. Despite these uncertainties and conflicting trends there seems to be a general agreement that the demand for fuelwood is not going to change rapidly (Solberg 1996; FAO 2003b). Energy efficiency improvements (e.g. improved stoves or the use of modern bioenergy carriers such as liquid fuels) on the other hand have (in theory) the potential to more than offset increasing demand up to 2030.

Data from existing studies indicate a consumption of fuelwood between 1,7 billion $m^3$ in 2050 and 2,5 billion $m^3$ in 2020 (Nilsson 1996; Solberg 1996; IMAGE-team 2001; FAO 2003b) see Appendix G), compared to the present ca. 1,8 billion $m^3$ (FAO 2002a)

*Calculations*

Given the large range in estimates, no most-likely scenario was included. The upper range of projections of the consumption of fuelwood is used as a high scenario, the low range of projections as a low scenario, the medium scenario is the average of the low and high scenario. The three scenarios are based on the total global consumption of fuelwood. The fuelwood consumption in each region (based on projections to 2030 received from the FAO) as a percentage of the total global consumption is used to allocate the (three projections of) global fuelwood consumption to the different world regions.

*Output*

Three scenarios are included which represent the broad range in consumption forecasts found in literature.

- The low scenario is set at 1,8 billion $m^3$ representing the lower range of projections found in literature.
- The medium scenario is the average of low and high scenario
- The high scenario is based on 2,9 billion $m^3$ based on constant per capita fuelwood consumption and the increase in population. Note that trend extrapolation of data from the Global Forest Products Model to 2030 (FAO, provisional and unpublished data, 2003) indicates a consumption in 2050 of 3,2 million $m^3$. However, an increase in the per capita consumption is unlikely, so a constant per capita consumption is included as a high scenario.

## 3.3 LAND USE FOR CROP PRODUCTION

The efficiency of production (the yields) is the most important factor for land use patterns (Döös and Shaw 1999; FAO 2000a).Yields are determined by the natural circumstances (temperature, solar radiation, rainfall, day length etc.) and management system. Natural circumstances are assumed constant (the effects of a possible climate change and effects on agriculture are excluded). Only in the case of expansion of agricultural land use and shifts in production patterns within the current agricultural land use, the natural circumstances are important, because soil quality and climate are not equally suitable for different crops.

The applied level of agricultural technology and changes in agricultural land use in a certain region are determined by a complex system of interactions, which involves the entire socio-economic situation (e.g. prices of land and labour, available infrastructure, interest rates, education level of agricultural workforce etc.). These interactions are not well understood (Döös and Shaw 1999; IFPRI 2001b) and are beyond the scope of this paper. Two approaches have been followed to "circumvent" this issue: FAO projections on consumption and agricultural land use are used as a most likely scenario. Secondly, several calculations (scenario's) are included that illustrate the impact of the applied level of agricultural technology on the land use patterns.

### 3.3.1 FAO projections

As a *'most likely'* scenario the increase in yields and area cropland projected by the FAO in the report 'World Agriculture: Towards 2015-2030' (FAO 2003b) supplemented by data from the International Food Policy Research Institute (IFPRI 2001c) and USDA (USDA 2001)[8] is included.

The FAO projections are based on a combination of modelling methods. They start with Engel demand functions that include the correlation between income and food expenditures. Exogenous assumptions on population and GDP are used to project demand. Simple assumptions about the future self-sufficiency and trade levels are used as an entry point to project production levels. These projections go into several rounds of iterations in collaboration with FAO specialists on different countries and disciplines and using e.g. crop productivity maps. In several iterative rounds, it is estimated what is acceptable or feasible, notably with respect to issues as the average daily calorie intake, yields, land use, diet composition and trade. In addition, a price-flex models is used for oilcrops, cereals and livestock products to provide starting levels for iterations and to keep track of changes in variables. The model is a partial equilibrium model, consisting of single commodity modules and world market feedbacks leading to national and world market clearing through price adjustments.

The result is described as '*a set of projections that meet conditions of accounting consistency and to a large extend respect constraints and views expressed by the specialists in the different disciplines and countries*' (FAO 2003b). The projections try to indicate a *most likely scenario* based on current trends, but the projections are clearly *not trend extrapolations* or indicate actions that need to be taken to reach targets as e.g. the target of reducing the number undernourished people with 50% by 2015, set during the World Food Summit in 1996.

The FAO projects that in the coming three decades the area cropland increases significantly in most of the developing regions (figure 5) [9].

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8 The WATO 2015/30 report may be considered as the most influential and detailed study on the long-term future of agriculture presently available. This does not mean that the FAO projections are free of error or that the conclusions are undebated. Further, the FAO has a somewhat technological optimistic view on the capacity of the earth to meet the growing demand for food. There are also many studies that have a much more pessimistic view on the earth' carrying capacity and which highlight the effect of various forms of environmental degradation (e.g. Brown, 1997). Appendix P gives an overview of past projections, projection errors and more pessimistic studies.

9 An other potential source of land for bioenergy is degraded land. The future potential from degraded areas is difficult to calculate, due to a lack of reliable data on the extend degraded land. Statistics on arable land use provide little information, since these only indicate *net* changes in area, thereby

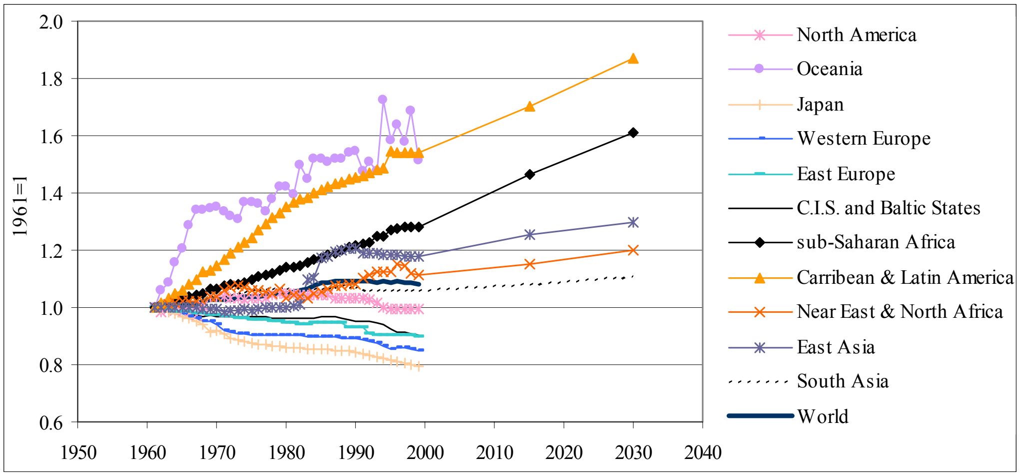


*Figure 5.* Area arable land 1961 to 2030. Sources: (FAO 2002a, 2003b).

The data are shown to indicate that that agricultural land use in the developing regions is likely to increase. Much of the increase in arable land is likely to come from deforestation as is also projected by other studies (e.g. by the implementation of the SRES scenarios in the IMAGE model). Expansion of agricultural land is the main reason for deforestation. In this study, deforestation is not allowed, so any land use changes occur only within the land area not under forest cover.

The FAO states that in the industrialised regions and transition economies, roughly a constant or marginally decreasing area arable land can be expected (FAO 2003b). This would mean a further continuation of trends from the last decades is in line with figure 5 that shows that in most of the industrialised regions and transition economies the area arable land decreased during the last decades. Based on the total demand for biomass, a (continued) decrease in arable land in the industrialised countries is more likely in West Europe, East Europe, C.I.S. & Baltic States and Japan than in Oceania and North America. In West Europe and Japan the population is expected to decrease (although this effect is slightly offset by increasing per capita consumption levels) while in Oceania and North America the population is expected to increase 35% and 47% to 2050 respectively. A relatively low increase in yields in West Europe, East Europe, C.I.S. & Baltic States and Japan results in a decreasing area cropland. However, a potential decline in the area arable land could be partially offset by emerging trends towards de-intensification in agriculture and the increasing demand for ecologically produced crops (without or with minimum use of fertilizers and chemicals).

Pastures are not included in the FAO calculations, although the FAO states that *globally* areas pastureland are likely to decrease due to increasing mixed farming, improved pastures and stall-fed systems, although the demand for animal products in the developing countries increases much stronger than in the industrialised regions. Figure 6 shows an overview of pastureland areas between 1961 to 2000 according to the FAO (FAO 2002a).

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excluding degraded areas from shifting agricultural land use. Current estimates of the area degraded indicate a significant global potential of 1.7 Gha maximum. The potential of these areas is however rather uncertain. See Hoogwijk (2003) for a review of estimates of bioenergy production potentials from degraded land.

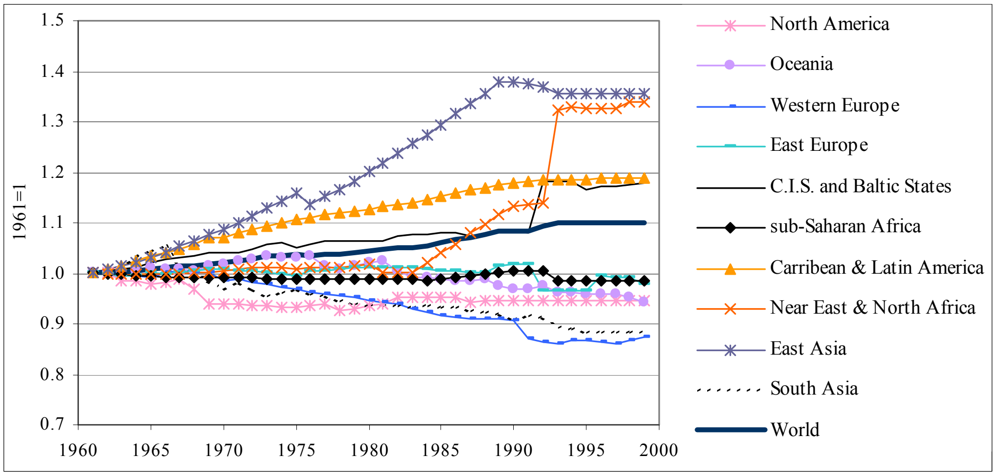


*Figure 6.* Area pastureland 1961 to 2000. Source: (FAO 2002a).

Note that sudden changes in area pastureland are most likely due to revision of the statistics or change in definitions instead of real changes. The pasture area is Japan is roughly 40% in 1998 compared to 1961 (data not shown).

### 3.3.2 The impact of agricultural technology

We calculate future land use patterns using an Excel spreadsheet tool. This Excel spreadsheet tool translates the projected demand for food into agricultural land use based on geographic optimalisation of land use and based on various levels of technology.

*Input*

The Excel spreadsheet uses three input datasets:

- Data on present harvested areas, yields, total arable land and various other land use categories are derived from the FAOSTAT database (FAO 2002a).
- Data on present and future consumption are based on the demand scenarios discussed in section 3.1.
- Data on yields and areas suitable for crop production if a certain level of technology is applied, are based on a crop growth model from the International Institute of Applied Systems Analysis (FAO 2002b). The basic data for the crop growth model consist of several maps on soil characteristics and climate, following the agro-ecological zones (AEZ) methodology. Data are given for five levels of technological development (FAO 2003b), defined as follows.
    - *Low, rain fed*: using no fertilizers, pesticides or improved seeds, equivalent to subsistence farming (as in rural parts of e.g. Africa and Asia).
    - *Medium, rain fed*: some use of fertilizers, pesticides, improved seeds and mechanical tools.
    - *High, rain fed*: with full use of all required inputs and management practices as in advanced commercial farming (comparable to (industrialised) production systems commonly found in the US and EU).

- *Very high*[10]*, rain fed*: use of high level of technology on very suitable and suitable soils, medium level of technology on moderately suitable areas and low level on moderately and marginally suitable areas. The rationale for allocation is that it is unlikely to make economic sense to cultivate moderately and marginally suitable areas under the high technology level, or to cultivate marginally suitable areas under the medium technology level.
- *Very high, rain fed and/or irrigated*: same as a very high input system, but including the potential effect of irrigation. No data were available on the actual percentages of the areas under irrigation, only data on total area cropland are given.
- *Super high*: the high and very high level of technology described are based on the best available technologies and exclude the impact of future technological improvements. We estimated that new technologies may increase yields by 25% above the very high production system, based on the analysis described below.

Thus, the data in the low, medium, high and very high production systems are based on both the natural circumstances and the level of agricultural technology. The crop specific datasets include the yield and area per country based on the classification of suitability for crop growth. The classification is based on the maximum constraint free yield (MCFY): very suitable (VS, 80-100% of MCFY), suitable (S, 80-100% of MCFY), moderately suitable (MS, 80-100% of MCFY), marginally suitable (mS, 20-40% of MCFY) and not suitable (NS, <20% of the MCFY)[11]. No yield levels are included for areas classified as NS. A data that indicates the total extend cropland available for crop production was also included. In total, data for 19 different crops are included. Further details of the datasets used are described in Appendix H.

Yield levels of the super high production system are 125% of those in the very high production system, because it is likely that agricultural technologies will continue to become more efficient and productive. The increase in yields is projected to occur at a much slower pace than observed over the past three decades. Quantum leaps from the order of magnitude as the Green Revolution are unlikely (excluding the impact of biotechnology[12]). The Green Revolution was aimed to reduce hunger in the developing regions by replacement of old agricultural traditions in developing regions with newer Western practices. Particularly the application of genetically engineered cereal varieties with higher grain to total plant biomass ratios (in combination with the application of irrigation and prolific quantities of fertilizer) made rapid increases in yields and production possible. The increases in yields and production resulted in decreasing world food prices during the last decades and declining investments in fundamental agricultural research, rural infrastructure (Evans 1998; IFPRI 2001c) and a shift in research and development to more

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[10] In the original IIASA classification, this production system is named 'mixed input system'. To avoid confusion with the term 'mixed' animal production system (section 3.4), a mixed production system is dubbed a 'Very high' production system, because it is generally the production system with the highest production potential.

[11] Because classification VS to mS is based on percentage of maximum constraint free yield (MCFY), not the absolute level of yields, a certain economic optimalization of production is included in this dataset. A VS yield in region 1 can be lower than a VS yield in region 2, but are equally important in the allocation procedure. Production in region 1 on VS areas is however attractive considering the relative high suitability compared with areas in that region.

[12] The impacts on yields and use of inputs due to the use of genetically modified organisms (GMO's) and their public acceptance and safety is not included in this assessment because of the very insecure future. When GMO's live up to their expectations the future of agriculture may be very different than the picture sketched above. The theoretical possibilities of genetic modification is unparalleled. E.g. the photosynthetic efficiency of an average potato field is the U.K. is presently 0.4%, while the theoretical efficiency (if all photosynthetic active radiation is absorbed) is 4.5%.

sustainable forms of agriculture instead of fundamental research aimed at increasing productivity. However, the aggregated impact of various technological developments is likely to result in an increase in yields. Some of the most important recent developments and research fields are summarised below (Evans 1998):

- Use of improved seed coatings with (macro)- and micronutrients, peroxides to provide oxygen and other chemicals to produce.
- Use of better fertilisers formulations and nitrification inhibitors to improve N uptake; only 30-70% is taken up by crops.
- Continuous improvement in means of reducing pests and diseases. Development of high activity chemicals allowing ultra-low volume spraying, development of resistant varieties, biological control agents, specific additional chemicals such as growth inhibitors, hormones, behaviour-modifying semiochemicals.
- Precision farming (also known as farming by soil, or satellite, site specific management, using site specific data allowing optimized management inputs.
- Improvement of the harvest index. One of the few quantitative projections found in literature is the theoretical maximum harvest index, estimated at 0.65 for cereals, compared to the current 0.4-0.45. Consequently, yields may further increase some 40%.

A quantification of the impact of the technologies described above is difficult. We *assume* that the crop yields may increase by 25% above the very high input system, which seems moderately compared to the 40% increase in yields solely from increasing the harvest index or the (theoretical) possibilities of biotechnology. The suitability of land areas and the feed conversion efficiencies are assumed constant, since we could not find estimates for this. In addition, IMAGE projections indicate that feed conversion efficiencies do (generally) not decrease below the feed conversion efficiency values of the high input of technology system defined in this study. Note that this may underestimate the impact of future technological developments, since e.g. the FAO concludes that '*a further understanding of digestive physiology and biochemistry can be expected to improve feed utilisation*' (FAO 2003b).Thus, the true theoretical potential for bioenergy is likely even higher than the super high production system.

*Calculations*

The Excel spreadsheet tool calculates how much land is needed to produce the demand for crops depending on the technology level and chosen allocation rules. A certain demand for crops can be produced for different combinations of yield and area; a small area very productive land can produce the same amount of crops as a large area low productive land.

In the Excel tool 24 allocation steps were used to allocate production to land use. One allocation step involves the allocation of the demand for 19 crops to yield-area combinations for one suitability class. First, all VS areas are used (as far there is a demand), followed by S, MS and mS. After one allocation step the remaining areas suitable for crop production, crop specific suitable areas and remaining demand go into a next round of allocation. For each suitability class (VS to mS) 6 allocation steps were used.

An example of the allocation process is shown in box 1. Box 1 shows a simplified version of the spreadsheet tool. In total data for 19 different crops[13] are included and 24 allocation steps are used.

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[13] The 19 crops represent 85% of the total harvested area of cereals, roots and tubers, sugar crops, oilcrops, pulses, fruit and vegetables, stimulants and spices and 65% of the total arable land and land use for permanent crops. Results show that the area cropland of the 19 crops included in this study may decrease dependant on the management system (section 4), so this may also be the case for the crops not included

**Box 1. Land allocation procedure**

Figure 7 shows how the allocation method works with data for two crops. Data on the area VS (very suitable), S, MS (moderately suitable) and mS (marginally suitable) and corresponding yields are shown in figure 7. The crop specific datasets provide no information to what extend e.g. the VS areas of the different crops overlap. Therefore, a third dataset is included that indicates the total extend land available for crop production (column on the right). All data shown are specific for a certain production system., see figure 7.

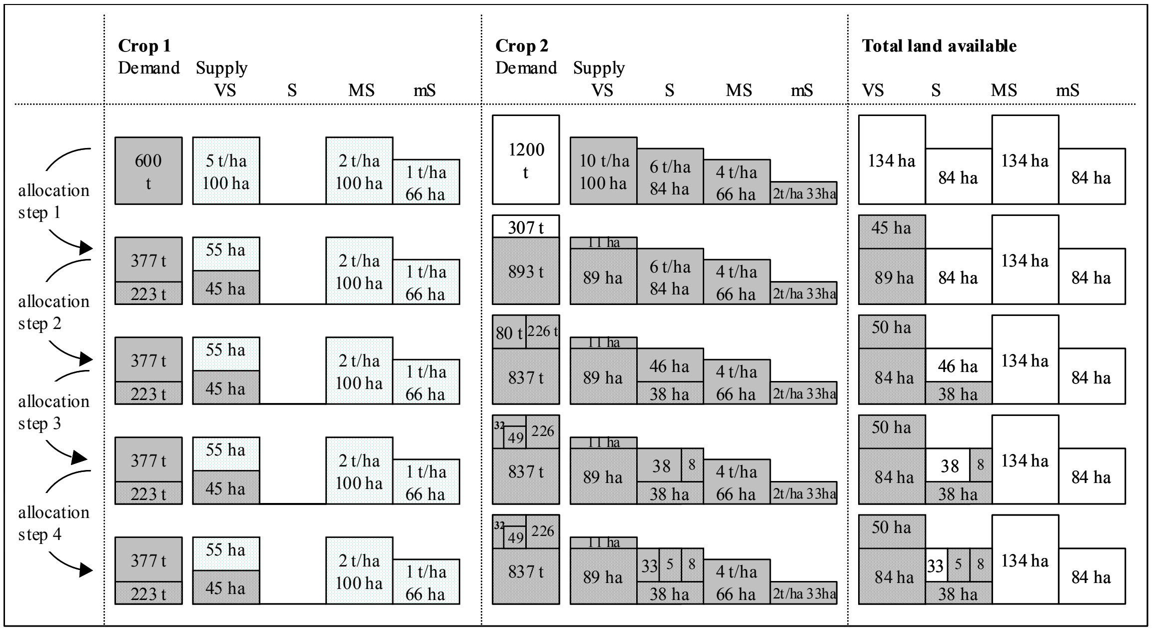


*Figure 7*. Principle of the land use allocation tool, see text for explanation. VS = very suitable, S = suitable, MS = moderately suitable, mS = marginally suitable.

Each allocation includes three calculations:

1. The allocation for each crop starts with the calculation of the percentage of the dry weight (DW) of the total DW demand for food and feed. This percentage determines the share of the total area suitable for crop production (not crop specific) that is available for that crop. The total area suitable for total crop production is the area where *at least* one crop can grow. The use of the percentages of total DW is necessary to allocate the crop land to the different crops more evenly, compared to a situation where one crop is simply giving priority above another. It also avoids overestimation of the land use, since in the example e.g. the VS area of crop 1 and 2 is 100 ha and 100 ha, while the total area is only 134 hectares (ha). There is an overlap in the VS area of crop 1 and crop 2.
2. Determine if the area calculated in step 1 is larger or smaller is than the crop specific area available for crop 1 and 2. The smallest area is the area that is used as input in step 3.
3. Determine if the area required to the meet demand is larger or smaller than the area calculated in step 2. The smallest of the two areas is the area that is being allocated.

In the example the allocation is as described below.

**Step 1**. Allocation of the demand to VS areas.

1. The total area available for crop 1 and 2 is respectively 600*100*134/(600+1200)=45 ha and for crop 2 1200*100*134/(600+1200)=89 ha (if the moisture content is the same for both crops, if not the demand must be multiplied by the moisture content). The VS areas of the two crops add up to 200 ha, which is more than the total VS area available (134 ha). Thus, there is 66 hectares overlap in VS area between crop 1 and

in this study. However, to avoid overestimation of the potential to grow bioenergy this area is taken constant.

crop 2. Thereby we assume that the overlap between crop 1 and 2 is minimal so that the total area is completely utilised. In theory, the overlap in VS area can be 100% (for both crops the VS area is 134 ha).
2. For crop 1 and crop 2 the crop specific areas suitable for crop production are larger than the areas allocated, so the total area available for crop production is the limiting factor. Crop 1: crop specific area is 100, but the total area available for crop 1 is 45. Crop 2: crop specific area is 100. The total area available for crop 2 is 89.
3. Determine the required area to meet demand. For crop 1 and 2 this is respectively 600/5=120 ha and 1200/10 = 120 ha. In both cases the total area available for production of crop 1 and 2 is the bottleneck.

**Step 2**. After allocation step 1 there is no total VS area left any more, so the allocation continues with the S areas. In the actual model, step 1 is repeated six times.
1. The total area available for crop 1 and 2 is respectively 377*100*84/(377+307)=46 ha and 307*100*84/(377+307)=38 ha.
2. For crop 1 the crop specific area (S) is 0. For crop 2 the crop specific area (S) is 84, so the total area available is the limiting factor and not the crop specific area.
3. The area required to meet demand is (307/6)=51 ha. The total area available for crop production is the bottleneck.
**Step 3.** Allocation of the remaining demand to the remaining S areas. There are still S areas left (both total area and crop specific area).
1. The total area available for crop 1 and 2 is respectively 377*100*84/(377+307)=46 ha and for crop 2 307*100*84/(377+307)=38 ha.
2. For crop 1 the crop specific area (S) is 0. For crop 2 the crop specific area (S) is 84, so the total area available is the limiting factor rather than the crop specific area.
3. The area required to meet demand is (307/6)=51 ha. The total area available for crop production (46 ha) is the bottleneck.
**Step 4.** Allocation of the demand to S areas. In allocation step 2 and 3 the potential to produce crops on S land is not fully used. There are still S areas left, both total area and crop specific area.
1. When after 5 rounds of allocation (only two are shown here) there is still a potential for a certain land use class to meet the demand (as is the case now for S areas), step 1 is left out. The allocation simply starts with crop 1, than crop 2.
2. For crop 1 the crop specific area (S) is 0. For crop 2 the crop specific area (S) is 38 ha.
3. The area required to meet demand is (38/6)=5 ha. The total required area is the bottleneck (5 ha).
**Step 5 and further**. Allocation of the remaining demand to MS and mS areas is based on the same steps described above, data are not further shown.

The allocation of demand to yield-area combinations as shown in box 1 is done per region. After 24 allocation steps, some regions may have a self-sufficiency ratio (SSR) below 100%. The SSR is defined as the ratio between the total dry weight of the demand allocated and the total dry weight of the demand (in %). The remaining total demand in various regions is allocated to regions that have a remaining production potential and again all 24 allocation steps are used to allocate the remaining demand. In reality, a SSR below 100% indicates that trade is applied to meet regional food shortages. The allocation process is repeated three times in total. If after three times there is still a food shortage (compared to the projected demand), the potential to grow bioenergy is assumed zero.

The calculated area cropland required to produce the crops included in the model is compared to the area *arable land* in the base year. By definition, an increase in the area cropland and/or area permanent pasture is not possible, since deforestation is not allowed. The calculated areas are compared to the area arable land, not the harvested areas, since the harvested areas provide limited information on the total agricultural land use[14]. Note that not all crops are included in the

[14] The FAO STAT database provides data on harvested land (per crop) and total arable land in agricultural use. Data on total harvested land can be obtained by summing up the harvested areas reported for different crops. These datasets are not necessarily compatible. Differences are caused by double

spreadsheet tool. The future land use for crops not included in the model is taken constant to avoid overestimation of the land available for bioenergy production.

*Output*

The result of the model are data on the average potential to increase yields and decrease the area arable land.

The allocation procedure could over- or underestimate the production potential. An overestimation occurs when the productive area of most crops overlap, but there is one crop with a large productive area so that the total productive area is exaggerated and reflects more productive area of the one crop than the total of all crops. An underestimation is possible when the aggregation of the yield area data from country to regional data results in less optimized allocation compared to country level allocation procedures. Further, the allocation procedure is based on the regional average yields and regional available areas. If production is optimized (allocated to the most productive areas) globally, the potential to increase yields will be higher than estimated in this study.

An other cause for overestimation is the exclusion of the impact of various forms of environmental degradation, notably soil erosion and fresh water shortages (see also section 6 and Appendix Q for a short introduction one of the potentially largest threats to global agriculture: soil erosion). However, there is a general agreement that '*most forms of environmental degradation and overuse are caused by an improper use of resources or can be reduced or prevented by an appropriate mix of policies and technological changes'* (e.g. (UN 1993; Alexandratos 1994)). In this study, the focus is on the technical potential, so we exclude the impact environmental degradation due to inappropriate use of resources rather than production itself.

## 3.4 Land use for the production of animal products

The consumption of animal products is identified as a major land use factor because the consumption of meat is expected to increase rapidly and the production of animal products is more land intensive per kcal produced than crop production. The production efficiencies of animal products measured in land areas is influenced by the feed conversion efficiency (efficiency with which feed is converted into animal product) and the efficiency of feed production. The demand for feed per kg animal product ranges between 3 to more than 100 kg dry weight biomass input per kg meat, dependant on the quality of the biomass inputs, type of animal(product) and the management system (e.g. use of specialised breeds, industrialised production systems vs. pastoral production systems). In general, more efficient production systems use more concentrated feeds and less grazing and scavenging biomass.

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cropping (harvested areas are included twice in harvested areas statistics), areas sown but not harvested (included in arable land but not in harvested area), small uncultivated patches, footpaths, ditches, headlands, shoulders, shelterbelts, etc. (not included in harvested areas). The cropping intensity (CI, defined as the ratio harvested land to arable land) can be used to evaluate the compatibility of the two datasets. Globally the area harvested is 93% of the area arable land, regional aggregated data are between 63% in Latin America & Caribbean and 130% in East Asia (FAO, 2003). In this study, the calculated areas are compared to the arable land, thereby assuming a cropping intensity of 100%. Thus, in some regions, a considerable potential to increase production comes from increasing the CI to 1.

The latest FAO projections to 2030 indicate the change in area cropland and pastureland to 2030 (FAO 2003b). Alternatively, the effect of technological developments is included in this study as described below.

*Input*

Various datasets are used as input for the calculations:

- data on the demand for animal products are based on the food consumption scenarios (section 3.1).
- data on feed conversion efficiency, feed composition and the type of animal production system are derived from a study on current and future feed conversion efficiencies for the IMAGE model (Bouwman *et al.* 2003)[15]. Note that the data on feed conversion efficiency, feed composition and the production system are correlated as described below.

*Calculations & analysis*

A wide variety of products is used as feed in the animal production system. Feed categories included in this study are classified as grasses & fodder, feed from crops and residues & scavenging. The demand for feed category (f) is calculated based on the demand for animal products type (c) in region (r), the production system (p) (pastoral vs. mixed), feed conversion efficiency and consumption of the feed diet, see the formula below.

$Feed_{cfpr} = Demand_{cr} \times Prod_{cr} \times Fce_{pr} \times Fco_{cfpr}$

- $Demand_{cr}$ = demand for animal products taken from the consumption scenarios.
- $Prod_{cr}$ = production system. Three production systems are defined:
  - Pastoral production system. In a pastoral system, most feed comes from grazing (permanent pastures) and scavenging.
  - Landless (industrialised) production system. This is the opposite of a pastoral production system. All animal are kept inside in stables and all feed comes from feed crops[16] and residues.
  - Mixed production system. A mixed production system is a combination of a landless and pastoral production system.

  In general, the highest feed conversion efficiency is reached in landless, industrialised production system, the lowest in pastoral systems. This indicates that the production system, feed composition and feed conversion efficiency are linked.
- $Fce_{pr}$ = feed conversion efficiency. In this study the feed conversion efficiency is defined as the production of animal product per kg biomass input (dry weight). Feed conversion efficiency data obtained from the IMAGE team are specified per region, production system (pastoral and mixed) and type of animal product (milk, beef, pig meat, goat meat, poultry meat, eggs). The *range* in feed conversion efficiencies for the year 1995 is used to estimate the feed conversion efficiencies in a low, medium and high level of technology (see definitions in section 3.3.2). Data for the production system 2050 are included in the dataset. No data were available for the feed conversion efficiencies of a landless production system, so data of the mixed production system were used. Table 1a shows the inverse of feed

[15] The Integrated Model to Assess the Global Environment (IMAGE) is a dynamic integrated assessment modelling framework for global change. The main objectives of IMAGE are to contribute to scientific understanding and support decision-making by quantifying the relative importance of major processes and interactions in the society-biosphere-climate system (IMAGE-team, 2001).

[16] Feed crops are defined as crops also suitable for human consumption, excluding e.g. alfalfa.

conversion efficiencies (feed demand per kg animal product in 1995 (IMAGE-team 2001). Table 1b shows the feed demand per kg animal product ($Fce^{-1}$) of a mixed and pastoral production system based on a low and high level of technology. The Fce's for a production system with a medium level of technology is the average of high and low level of technology. The data are shown to indicate the large potential to decrease the feed use per kg animal product (increase the Fce) in many regions.

- $Fco_{cfpr}$ = feed composition. Data on feed composition are specific for each region, type of animal product and production system. The dataset from the IMAGE model includes data on the present and future feed mix (grasses & fodder, feed from crops, residues and scavenging). The feed composition in a production system based on a low, medium and high level of technology is estimated based on regions with feed conversion efficiencies based on a low, medium and high level of technology (Appendix I).

*Table 1a.* Feed demand per kg production in 1995 (inverse of feed conversion efficiency; kg dry weight feed/kg product). Sources: (Bouwman *et al.* 2003; FAO 2003b), own calculations.

| region | bovine meat<br>kg/kg | milk<br>kg/kg | mutton & goat meat<br>kg/kg | pig meat<br>kg/kg | poultry meat and eggs<br>kg/kg |
|---|---|---|---|---|---|
| North America | 26 | 1.0 | 58 | 6.2 | 3.1 |
| Oceania | 36 | 1.2 | 106 | 6.2 | 3.1 |
| Japan | 15 | 1.3 | 221 | 6.2 | 3.1 |
| West Europe | 24 | 1.1 | 71 | 6.2 | 3.1 |
| East Europe | 19 | 1.2 | 86 | 7.0 | 3.9 |
| C.I.S. and Baltic States | 21 | 1.5 | 69 | 7.4 | 3.9 |
| sub-Saharan Africa | 99 | 3.7 | 108 | 6.6 | 4.1 |
| Caribbean & Latin America | 62 | 2.6 | 148 | 6.6 | 4.2 |
| Near East & North Africa | 28 | 1.7 | 62 | 7.5 | 4.1 |
| East Asia | 62 | 2.4 | 66 | 6.9 | 3.6 |
| South Asia | 72 | 1.9 | 64 | 6.6 | 4.1 |
| World | 45 | 1.6 | 79 | 6.7 | 3.6 |

*Table 1b.* Feed conversion efficiencies in a low and high input system (kg dry weight feed/kg product). Sources: (Bouwman *et al.* 2003; FAO 2003b).

| production system | level of technology | bovine meat<br>kg/kg | milk<br>kg/kg | mutton & goat meat<br>kg/kg | pig meat<br>kg/kg | poultry meat and eggs<br>kg/kg |
|---|---|---|---|---|---|---|
| mixed=landless | high | 15 | 1.0 | 46 | 6.2 | 3.1 |
| mixed=landless | low | 60 | 3.0 | 125 | 7.5 | 4.1 |
| pastoral system | high | 37 | 1.4 | 58 | n/a | n/a |
| pastoral system | low | 125 | 4.5 | 150 | n/a | n/a |

*Output*

The result of these calculations is a projected demand for animal feed in 2050. Each of the three different feed crop categories is translated into land use:

- grasses & fodder: a decrease in demand for feed from pastures and fodder is assumed to lead to a corresponding decrease in the demand for pasture biomass. An increase in demand is added up to the demand for feed from crops (the areas permanent pasture is not allowed to increase since deforestation is not allowed and higher grazing intensities are considered unsustainable).
- feed from crops: the demand for feed from crops is added to the demand for food crops and is included in the spreadsheet tool used to calculate land use.

- feed from residues & scavenging. No land use is allocated to feed from residues and scavenging, but the demand is included in the estimates of residues available for bioenergy.

Note that due to differences in the definition of regions between IMAGE data and the regional breakdown used in this study, data for 2050 and present come with a considerable uncertainty.

## 3.5 LAND USE FOR WOOD PRODUCTION

The different scenarios for the consumption of industrial roundwood are compared with the global wood production potential without regional of global supply and demand matching (both supply and demand are considered static). Reasons for this approach are:

- A lack of data and consensus on the earth' (sustainable) wood production capacity.
- A lack of data on the (regional) wood supply situation.
- Supply and demand matching is (partially) included in consumption scenarios. This means that the three demand scenarios are all considered plausible and that the demand is expected to be met.

Industrial roundwood production comes from very different sources and production systems, ranging from well-managed plantations to full deforestation of virgin forests. The same goes for fuelwood, except that large quantities of fuelwood come from trees outside the forest or from gathering of twigs and branches (for both no land use is taken into account).

### 3.5.1 Plantations

*Input*

In a report of the FAO Forestry Department, future plantation establishment rates wood supply from plantations to 2050 are estimated (FAO 2000c). Three scenarios are included that differ with respect to the assumed net rate of plantation establishment and yields. No demand and supply matching is included. The projected production of wood is based on the current species mix and includes the effect of plantation age structure.

*Calculations*

Data on plantation establishment rates are given for industrial plantations only. Data on future wood supply from non-industrial plantations are calculated based on the regional plantation establishment growth rates multiplied with the regional average yields and regionally aggregated plantation areas in the base year 1995. Non-industrial plantations produce fuelwood, although it is often difficult to identify whether these plantations are managed for fuelwood or for water or soil protection, recreation or similar non-productive purposes.

Note that the total plantation area accounts for only 5% of the forest cover, but that plantations supply 35% of the global roundwood consumption (FAO 2001). We did not attempt to include a most likely scenario for plantation establishment, but given the continued increase in plantation area in recent years, the medium and high scenario are the most likely. Further details on the plantation scenarios are shown in Appendix J.

*Output*

The three scenarios are:

- The low scenario assumes no growth in the plantation area (103 million ha industrial roundwood plantation area in 1995 and 20 million hectares non-industrial plantation area in 1995)[17].
- The medium scenario assumes an industrial plantation area in 2050 of 160 million hectares plus 32 million ha non-industrial forest plantations based on a fixed plantation establishment rate of 1% of the 1995 plantation area.
- The high scenario assumes a gradual reduction from current actual afforestation rates resulting in a industrial plantation area of 224 million (284 million ha assuming a similar increase in non-industrial plantation establishment)[18]. The FAO states this scenario seems to be achievable in physical terms and represents the upper boundary of new planting rates. However, such scenario would require a significant change in current thinking about ecology and desired forest practices. Particularly in Europe and North America, concerns arise to what extend plantations are beneficial from an environmental point of view (particularly with respect to possible negative impacts on water resources (FAO 2000c).

The regional plantation production potentials and yields are shown in table 2.

*Table 2.* Production and yields of wood from (industrial and non-industrial) plantations in 2050 for three scenarios. Source: (FAO 2000c), own calculations[19]).

| Region | Production Low plantation establishment $EJy^{-1}$ | Production medium plantation establishment $EJy^{-1}$ | Production high plantation establishment $EJy^{-1}$ | Yield low plantation establishment $Ejha^{-1}y^{-1}$ | Yield medium plantation establishment $Ejha^{-1}y^{-1}$ | Yield high plantation establishment $Ejha^{-1}y^{-1}$ |
|---|---|---|---|---|---|---|
| North America | 0.9 | 1.3 | 2.0 | 49 | 45 | 48 |
| Oceania | 0.3 | 0.4 | 0.5 | 102 | 93 | 97 |
| Japan | 0.2 | 0.3 | 0.2 | 19 | 16 | 18 |
| West Europe | 0.3 | 0.4 | 0.5 | 43 | 37 | 40 |
| East Europe | 0.0 | 0.1 | 0.1 | 39 | 35 | 40 |
| C.I.S. and Baltic States | 0.2 | 0.3 | 0.2 | 9 | 8 | 9 |
| sub-Saharan Africa | 0.2 | 0.2 | 0.3 | 52 | 47 | 37 |
| Caribbean & Latin America | 0.6 | 0.9 | 1.4 | 72 | 65 | 63 |
| Near East & North Africa | 0.1 | 0.1 | 0.2 | 19 | 18 | 20 |
| East Asia | 1.1 | 1.6 | 4.2 | 35 | 33 | 36 |
| South Asia | 0.6 | 0.9 | 1.7 | 48 | 44 | 46 |
| World | 4.5 | 6.4 | 11 | 37 | 34 | 39 |

The changing yields are caused by the skewed age structure of plantations. Once planted, it takes several years before plantations can be harvested. Therefore, production levels tend to be irregular, dependant on the historic plantation establishment pattern.

### 3.5.2 Natural forests

A difference between wood demand and the potential wood production indicates a wood gap or surplus. We assume that the gap is closed due to supply – demand interactions, since the there is a

[17] The areas refer to the *net* plantation establishment, thus excluding areas that were planted but failed to become productive plantations.

[18] New planting rates are based on annual rates of new planting in tropical and subtropical countries (Pandy, 1997). For temperate countries new planting rates were estimated. For the period 2005-2034 these planting rates are reduced to 20% of the current new planting rate, which is maintained to 2050.

[19] Based on 50% moisture content, 0.58 $t/m^3$ and a HHV of 20 $GJ/ton_{dw}$

general agreement that *'the technological global wood production capacity is sufficiently large to fulfil the largest projected increases in demand'* (EFI 1996). Further, standing stocks may serve as a buffer to reduce the effect of regional of temporary market fluctuations. The volume standing stocks is more than 120 times the current total wood consumption (FAO 2001, 2002a).

*Input*

Data on the annual forest growth of forests are based on data on the Gross Annual Increment data (GAI) derived from the Global Fibre Supply Model (FAO 1998b). Data on annual forest growth are very uncertain and there is a paucity of good data in this area (FAO 1997a). The total theoretical wood supply in this study is ca. 7 billion $m^3$; other studies estimate the total maximum supply at 7 to 9 billion $m^3$ (Steinlin, 1997 in (Müller 2001) and 11 billion $m^3$ (Sharma, 1992 in (Müller 2001).

Data on the forest areas were derived from the FAOSTAT database (FAO 2002a). To avoid overestimation of the production potential, the forest areas were divided into closed and open forest based on FAO's Forest Resources Assessment 2000 (FAO 2001). Further, open forests (discontinuous tree cover of 10 to 40%) are assumed to have a GAI of one fourth of that of closed forests (>40% tree cover).

*Calculations*

The production potential is estimated based on the present forest area and the annual forest growth. Excluded forest areas are legally protected areas according to IUCN classes 1 and 2 plus additional areas required to meet the goal of 10% protected area[20]. Deforestation is not allowed, because this is considered as an important criteria for a sustainable bioenergy production system[21].

*Output*

The result of these calculations give an indication of the global annual forest growth, regionally differentiated.

## 3.6 BUILD-UP LAND

*Input*

Detailed data on build-up land per capita are scarce and vary widely. E.g. estimates of the land use in China vary between 0.015 to 0.028 ha/cap, data for the U.S.A. vary between 0.025 to 0.143 ha $cap^{-1}$ (see Appendix K). Possibly, the large differences are partially the result of differences in definition and assessment techniques.

In this study we use data on build-up land from the IIASA database (FAO 2002b). This dataset was chosen because the areas build-up land were already subtracted from the areas available for crop production used to calculate crop land (section 3.7). The areas build-up land are also given per country. Note that the area build-up land is 1.2%, compared to ca. 2% reported by UNEP

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[20] 10% is a frequently used guideline for the protection of biodiversity (Soulé and Sanjayan 1998), originally proposed by the Union of the Conservation of Nature and Natural Resources in 1998.

[21] The primary cause of deforestation is clearance for agriculture, not the demand for wood (WRI 1999).

(UNEP 2002b). The cause of the difference is not know, but potential causes are differences in definition or data collection and estimation.

*Calculations*

The areas build-up land are summed up to regional aggregated data. The area build-up land is assumed to increase equal to the population growth, resulting in an increase to 1,8% of the total land area in 2050 (UNEP projects and increase of the area build-up land to 3 to 4% of the total area in 2030 (UNEP 2002b).

The impact on the production potential could however be much larger, because urban areas are often located near coastal zones and in river deltas. Expansion of cities often goes at the expanse of fertile soils. Therefore, we assume that the expansion of the area build-up land occurs at the expense of very suitable (VS) to moderately suitable (mS) areas. The demand for build-up area is allocated to the areas VS, S, MS and mS based on the percentage of the sum of the areas VS, S, MS and mS. Note that despite this impact, various studies that indicate that the *total* effect on agriculture is limited (e.g. IFPRI, 2001). Further discussions on urban land use are shown in Appendix K.

*Output*

The result of the calculations is a table with areas build-up land in 2050 and a table with the remaining areas VS to mS after these areas build-up areas are subtracted, see further section 3.7.

## 3.7 LAND USE ALLOCATION METHOD

In this study we use data about the areas suitable for crop production and the productivity of these areas to calculate a technical production potential and a minimal agricultural land use to meet the future food demand (FAO 2002b). Obviously, not all areas suitable for crop production are available for crop production. Significant areas are occupied by forests, build-up land or claimed for various other functions other than cropland. Except for forests and build-up land, the data on areas and productivity exclude information on the current land use or which crops are grown where. Georeferenced data (maps) and the use of Geographic Information Systems (GIS) software needed to build a GIS database and land use model could provide an outcome. Unfortunately, maps based on satellite data also come with considerable uncertainty resulting from the interpretation of the remote sensing data and the use of GIS software is considered too complex considered the limited time and resources available for this study.

Consequently, assumptions are required to what extend current land use overlaps with (potentially) productive cropland. This section explains how the areas suitable for crop production (VS, S, MS and mS) are allocated to the different land use categories (build-up land, forests, plantations etc.). In addition, the use of different allocation rules can be used to analyse the impact of different land use options or competition between land use categories. By definition, the size of all areas is equal to the 1998 area arable land, since deforestation is not allowed. In other words: a fictive land use ‘map’ is created indicating to what extend current agricultural land use overlaps with the areas VS, S, MS, mS and NS which follow from the IIASA datasets (FAO 2002b).

*Input*

Data on current land use are based on a modified version of the FAO land use classification and database (FAO 2002a) as described below. Data on plantation area are derived from an FAO study on plantation establishment (FAO 2000c). Build-up areas are derived from IIASA data (FAO 2002b).

*Calculations and output*

The following land use classification is used in this study (the numbers indicate the global areas in 1995 according to the FAO (FAO 2000b, 2002a) and own calculations as described below):

- *Other land* (3.6 Gha): land not included in the FAO land use categories permanent pastures, forests and woodland incl. plantations, arable land and permanent crops. Other land includes e.g. barren land. Data are based on the total land area minus the areas permanent pastures, forests and woodland (incl. plantations), other crops (all from FAO database) and build-up areas (IIASA database).
- *Permanent pastures* (3.5 Gha): land used permanently (five years or more) for herbaceous forage crops, either cultivated or growing wild (wild prairie or grazing land).
- *Build-up land* (0.2 Gha): land used for housing and infrastructure. Data are derived from the IIASA database.
- *Forest* (4.2 Gha): land under natural or planted stands of trees (excluding plantations), whether productive or not. This category includes land from which forests have been cleared but that will be reforested in the foreseeable future, but it excludes woodland or forest used only for recreation purposes. Data are based on the FAO land use category 'forests' minus the present plantation areas.
- *Permanent crops* (0.1 Gha) land cultivated with crops that occupy the land for long periods and need not be replanted after each harvest, such as cocoa, coffee and rubber; this category includes land under flowering shrubs, fruit trees, nut trees and vines, but excludes land under trees grown for wood or timber. Data are taken from the FAO STAT database.
- *Arable land* (1.4 Gha) land under temporary crops (double-cropped areas are counted only once), temporary meadows for mowing or pasture, land under market and kitchen gardens and land temporarily fallow (less than five years). Abandoned land resulting from shifting cultivation is not included in this category. Data on arable land are based on the FAO STAT database and sub-divided into:
    - arable land used for crops included in the spreadsheet tool (1.1 Gha), referred to as 'crops included in spreadsheet tool'
    - arable land used for crops not included in the spreadsheet tool (0.2 Gha), referred to as 'crops not included in spreadsheet tool'
    - arable land used for the production of fodder crops (0.2 Gha), referred to as 'fodder crops'.

  The sub-division is based on the percentage of the harvested areas of the crops included in each of the three categories of the total harvested area. Note that in the FAO database, the sum of harvested areas of different crops is not equal to the area arable land and a total harvested area is not given (see further section 3.3.2).
- *Agricultural land* (5.0 Gha) sum of permanent crops, arable land and permanent pastures.

The areas VS, S, MS, mS and NS are allocated to the different land use categories based on a set of allocation rules described below.

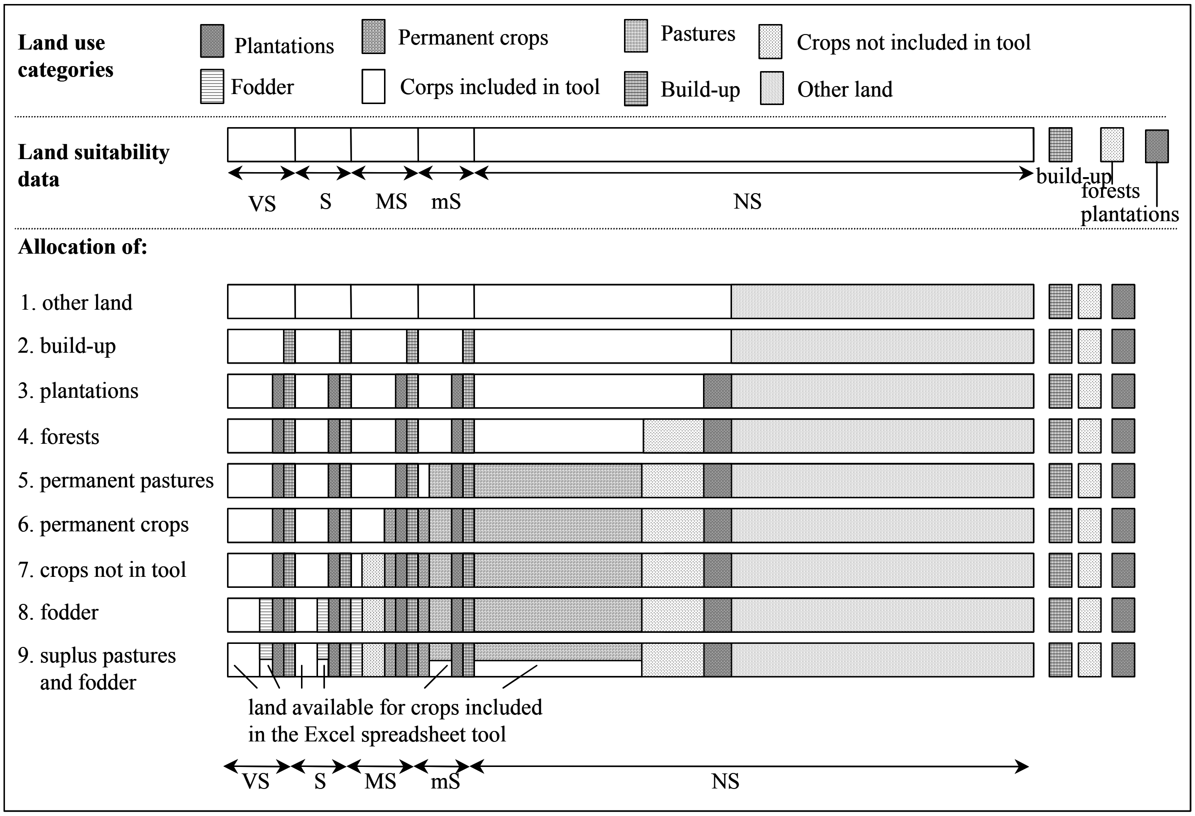



*Figure 8.* Allocation of (potentially) productive land to different land use categories.

Figure 8 gives an overview of the land allocation results for a fictive region. The two datasets are shown in the upper part of figure 8: the land use classification (data and classification based on FAO and IIASA data) and IIASA datasets on areas VS to NS for crop production.

The allocation rules used are:

1. The land use category *other land* is allocated to NS areas first, since this category includes barren land[22]. The remaining area 'other land' (if any), is allocated to mS, than to MS etc.
2. The areas VS to NS occupied by *build-up land* are already excluded based on the overlap between these areas as included in the different maps in the GIS database. The increase in build-up land to 2050 is allocated to the areas mS to VS based on the percentage of each suitability class of the sum of mS, MS, S and VS. The rationale for this is that expansion of infrastructure occurs generally on fertile soils.
3. *Plantations* are allocated to NS to VS areas, based on the percentage of the total area NS to VS. At least some of the current or new plantations are being established on areas suitable for crop production (FAO 2000c). The area NS was also included because:
   - non-industrial plantations (ca. 20% of the total plantation area in 1998) are mainly grown for wood fuel, but also for soil and water protection. Plantations on the latter type are typically situated on low productive areas.
   - the areas VS to NS are classified based on the suitability for crop production, not for the production of wood from plantations. The requirements for crops and tree species may be slightly different meaning that areas classified as NS for crop production can be used for plantation growth. Note that that the land use category 'other land' (including barren

[22] Burdingh and Dudall (1987) estimated that 18% of the land classified by the FAO as *'other land'* is prime agricultural land and 65% has a low to moderate production capacity.

land) is already excluded for the areas NS, meaning that the remaining NS area has at least some productivity. Further, the plantation yields used in this study are often lower than yields for high yielding plantations found in literature. This means that the plantation areas projected in this study may be reduced if proper management is applied.
- suitable cropland is generally more valuable if allocated to agriculture (FAO 2000c).

4. *Forests areas* are already excluded from the areas VS to NS used in this study. However, the forest areas used by the IIASA are lower than the FAO land use data, possibly due to differences in base year, classification or method of measuring. Additional forest areas are subtracted from the areas not suitable for crop production (if not available from mS, etc.)., because the classification VS to NS is based on the bio-physiological requirements of crops, not forests (see bullet 3 of the plantation allocation rules). Further, forests are remaining areas not suitable for agriculture due to steepness, soil structure etc.
5. *Permanent pastures* are allocated to NS areas (if not available they are allocated to mS, etc.), because the classification VS to NS is based on crops and not on grasses. Secondly, barren land is already excluded from the area NS, this indicates that the remaining land area is productive and may thus be used as pasture land. Thirdly, the land areas for permanent pastures is in many regions larger than the areas VS to mS, indicating that pasture areas are presently partially located on NS areas (see also table 4).
6. *Permanent crops* account for 9% of the total arable land (with a regional data are between 1 and 18%). Areas used for permanent crops are allocated to NS areas (if not available they are allocated to mS, etc.), because the suitability classification is not based on permanent crops.
7. Globally, *crops not included* (in the spreadsheet tool) account for 13% of the sum of the total harvested area (with regional variation between 5 and 20%). The allocation of VS to NS land to crops not included in the spreadsheet tool is based on the same allocation rule as for permanent crops.
8. *Fodder crops* are allocated VS to mS areas. The most important fodder crop is silage maize. We assume that the growth demand of silage maize is roughly similar to maize, so fodder crops require at least mS land. Fodder crops are allocated to mS to VS areas, based on the percentage of the total area mS to VS.
9. *Surplus areas permanent pasture* and arable land used for *fodder crops* are excluded based on the decrease in demand (if any) for permanent pasture and fodder.

The surplus areas permanent pasture and arable land used for the production of fodder crops are added up to the remaining areas productive land not yet allocated. These areas comprising of a combination of VS, S, MS and mS areas are the input of the Excel spreadsheet tool.

The impact of the allocation rules and assumptions is further analysed in the sensitivity analysis in section 5. We are aware that any of these allocation steps includes errors, but considering the goal (a global quick scan) and a time horizon of 50 years that makes large land changes and technological progress possible, we consider the allocation a suitable methodology, at least for the goal of this study.

## 3.8 Bioenergy yields

*Input*

We chose to use yield data for short rotation woody bioenergy crops (e.g. eucalyptus, poplar or willow) from the IMAGE model (IMAGE-team 2001). This dataset are derived from crop modelling and are based on the A1 SRES scenario. We use this dataset, because there is extensive experience with woody bioenergy for fibre production for the pulp and paper industry and woody biomass can be converted in various types of fuel (Hoogwijk *et al.* 2003). In addition, such data were readily available at a detailed level. Note that higher bioenergy yields in tropical regions are possible if herbaceous crops (e.g. *Miscantus*) are used (Hall *et al.* 1993).

*Calculations*

To be able to calculate the bioenergy potential based on the areas surplus land that are subdivided into VS, S, MS and mS and into different levels of technology, data on bioenergy yields must have a comparable subdivision. The original IMAGE classification was decreased from 50 to 5 (VS to NS) land suitability classes. The yield levels in a low and high input system are based on the yield level of bioenergy crops as projected by the IMAGE model in 2000 and 2050 following trend projected by the A1 scenario (strong increase in productivity). According to this scenario, bioenergy yields increase from 70% to 150% of the theoretically feasible yield (based on climate and soil conditions as simulated by a terrestrial vegetation model). This increase includes the effects of breeding, a higher harvest index, increasing use of irrigation and fertilizers, general technological improvements and the (very limited) effect of $CO_2$ fertilisation. We are aware that the various levels of technology defined in section 3.3.2 on bioenergy crop yields, may differ from the level of technology and management in the IMAGE data.

*Output*

The output of the calculations are three datasets for a low, medium and high level of technology similar to the data of crop 1 and crop 2 as shown in figure 7. Figure 9 shows the (modelled) yield – areas curve for the production of bioenergy, if a low and high level of technology was used.

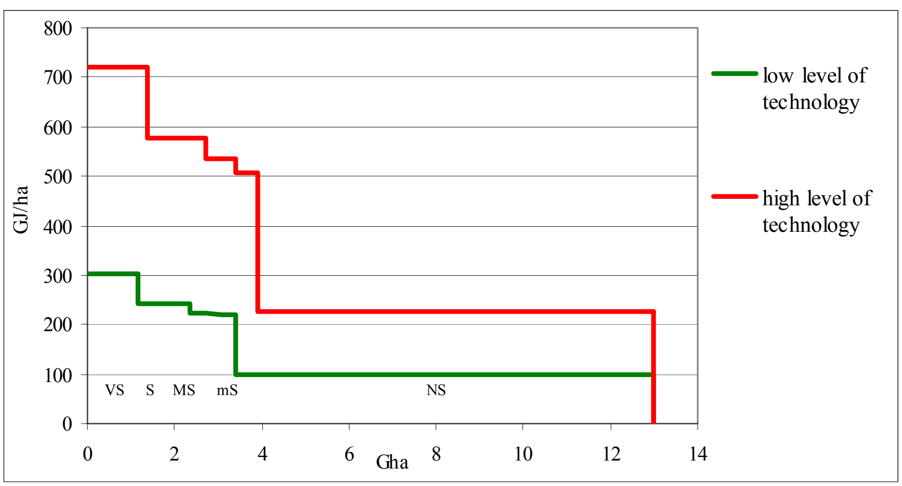



*Figure 9.* Simulated bioenergy yields (GJ/ha) based on a production system with a low and high level of technology (VS = very suitable areas, S = suitable areas, MS = moderately suitable areas, mS = marginally suitable areas). Source: (IMAGE-team 2001), own calculations.

The areas under the lines is the production potential for bioenergy. For a low and high level of technology this potential is 1807 and 4435 $EJy^{-1}$ respectively (based on a HHV of 19 GJ $ton^{-1}$ dw).

## 3.9 Residues and wastes

*Input*

Several datasets listed below are used to calculate the amount of residues and wastes available for bioenergy. All factors included are constant.

- The demand for food and wood is derived from the scenarios included in this study.
- *Processing residue coefficient* (PR) is the percentage of primary product available after processing (FAO 2000d, 2003a), see also Appendix L. Processing residues are also referred to as secondary residues.
- *Crop residue coefficient* (for crops, CR) or *harvest residue coefficient* (for roundwood, HR). The crop residue factor is 1-(1/harvest index). The harvest index (HI) is defined as the ratio between the part of the crop harvested and the total above ground biomass i.e. biological yield (e.g. in the case of cereals the part of the crops harvested are the grains of corn, usually some 40%). The crop residue coefficients are a function of the level of technology. High intensive production systems have higher HI's (and thus less residue production) than low intensive production systems. E.g. the HI of winter wheat is 0.45, 0.35, 0.25 in a low, medium and high input system respectively. Data on the current harvest residue coefficients are based on FAO data (FAO, unpublished data). Based on the range found in residue coefficients, coefficients for a low, medium and high level of technology are estimated (see Appendix L).
- *Post harvest losses* (pre end user losses) are calculated based on the FAOSTAT database (FAO 2003b). The database provides data on the current waste production and total production. The ratio between the two is dubbed the waste production coefficient (WA). A low, medium and high waste scenario based on the range in waste production in the base year.
- The *recoverability fraction* (RE) is the ratio between the residues that realistically can be collected and the total production of residues. The RE found in literature for crop harvest residues vary between 25% (for straw from cereals) and 67% (tops and leaves from sugar cane production). Most studies use a recoverability fraction of 25%, which is also used in this study. The RE of crop processing residues is 100%, which is the RE of sugar cane residues. The RE of logging residues varies between 25% and 50%, the latter value is used in this study. The values for the recoverability fraction of sawmill residues ranges between 33% to 75% (developed countries), we use a RE of 50% for all residues from the wood processing industry. All values are based on values taken from Hoogwijk *et al.,* (2002), which are based on various other studies.
- Data on the amount of *residues used for feed* (Feedres) are derived from the scenarios for the demand for feed. To avoid overestimation of the amount of residues available for bioenergy production, the use of biomass from scavenging is also excluded from the amount of residues available for crop production.

*Calculations*

Data on the production of harvest residues (Harvestres), processing residues (Procesres) or waste (Waste) in region (r) and crop or forest product type (c) is calculated based on the formulas below:

| | | |
|---|---|---|
| $Harvestres_{cr}$ | $= HR * RE * Demand_{cr}$ | (crops or wood) |
| $Procesrescrops_{cr}$ | $= PR * RE * (Food_{cr}. + Proc_{cr})$ | (crops) |
| $Procesreswood_{cr}$ | $= PR * RE * Demand_{cr}$ | (wood) |
| $Waste_{cr}$ | $= WA * RE * Demand_{cr}$ | (crops) |

The total amount of agricultural residues from crop c in region that is available for bioenergy production ($Res_{cr}$) is:

$Res_{cr} = Harvestres_{cr} + Procesrescrops_{cr} + Procesreswood_{cr} + Waste_{cr} - Feedres$

*Output*

The calculations show the amounts of agricultural and forestry residues that are available for bioenergy production. Note that limiting factors resulting from economic constraints (collection of residues and wastes may not always be economically attractive) or ecological constraints (residues are also used e.g. as fertilizers or to prevent soil erosion.

# 4. RESULTS

In section 4 a selection of results is presented. In section 4.1 the different scenarios are described which are used to analyse the potential for bioenergy production. Section 4.2 presents land balances for each region, that indicate the potential to increase the area agricultural land and land for crop production. Section 4.3 gives an overview of the surplus areas permanent pasture based on various management systems. Section 4.4 to 4.6 give an overview of the potential to increase yields (4.4), the surplus agricultural areas (4.5) and the final production potential for bioenergy (4.6). Section 4.7 and 4.8 discuss the potential contribution of bioenergy from forestry and residues respectively. In section 4.9 the biomass exporting potential is analysed by comparing the production potentials for bioenergy with estimates of the domestic energy demand in 2050.

## 4.1 OVERVIEW OF SCENARIOS

This study specifically focuses on the impact on land use of the level of technology used in the agricultural production system. A large number of variables for which scenarios and ranges are given are is included in this study, so theoretically a large number of scenarios can be composed. In this study, four scenarios are selected based on the following aspects:

- the amount of information presented is limited to keep the amount of data and results manageable.
- scenarios based on a level of technology that lead to food ‘shortages’ (indicating that the projected demand for food can not be met, not to be confused with under nourishment or hunger), are excluded. A shortage of a few percent is allowed to account for the suboptimal allocation procedure used to translate the demand into yield-area combinations and the use of average yields per grid as discussed in section 3.3.
- scenarios are based on a plausible combination of technologies. E.g. a scenario based on a high level of technology for the production of food crops and a low level of technology used in the animal production system (low feed conversion efficiencies) is considered illogical. Going from scenario 1 to 4, the efficiency of food production (expressed in hectares cropland required to meet the projected increase in consumption) increases, thus the area agricultural land claimed for food production decreases.
- the most important difference between the scenarios is the type of animal production system. This factor is specifically included because:
  - this factor has the largest impact on the bioenergy potentials.
  - the type of production system that is used does *not necessarily* relate to the level of technology used in other parts of the agricultural production system. However, in general there is a tendency towards the use of industrialised production systems (mixed and/or landless) in response to an increasing demand for feed and agricultural land.

The impact of various other parameters included in this study is analysed by means of a sensitivity analysis. Note that the mechanisms through which the various scenarios can become reality or the probability of these scenarios are beyond the scope of this paper.

*Table 3.* Overview of the scenarios included in this study.

| | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|---|---|---|---|---|
| Feed conversion efficiency | high | high | high | high |
| Animal production system used (pastoral, mixed, landless) | mixed | mixed | landless | landless |
| Level of technology for crop production | very high | very high | very high | super high |
| Water supply for agriculture (rain-fed = r.f., irrigated = irri) | r.f. | r.f./irri. | r.f./irri. | r.f./irri. |

Scenarios 1 to 3 have in common that they are based on:

- a medium population growth (from a total world population of 5.9 billion in 1998 to 8.8 billion people in 2050; section 3.1.1),
- a medium increase in per capita food consumption (from a global average of 2,8 Mcal $cap^{-1}$ $day^{-1}$ in 1998 to 3.2 Mcal $cap^{-1}$ $day^{-1}$ in 2050; section 3.1.2),
- a high plantation establishment scenario (from 123 million hectares globally in 1998 to 284 million hectares in 2050; section 3.5.1),
- a high level of technology for the production of bioenergy crops (section 3.8).

Scenario 4 is based on the assumption that research and development efforts may increase yields above the existing level of technology used in this study as e.g. in scenario 3. In scenario 4 crop yields are 25% higher than in scenario 3 due to general technological improvements which are not further specified.

## 4.2 POTENTIAL TO INCREASE THE AREA AGRICULTURAL LAND

Some analysts argue that the potential to increase food production is limited due to a lack of high quality soils (FAO 2003b). Table 4 shows a comparison of the areas cropland and permanent pasture in 1994 and the areas suitable for crop production. Indicated are the total areas cropland suitable for crop production in a very high input system, rain fed and/or irrigated (sum of VS, S, MS, mS areas; column I) and areas presently under forest cover (II). See section 3.3.2 for definitions of VS, S, MS and mS. Comparison of these areas with the areas arable land & permanent crops (IV) and total agricultural land use (V) is shown to give an *indication* of:

- the remaining potential of the natural resource 'suitable cropland' and the potential of a region to increase the production of both food and bioenergy and
- the validity of the results of the land use Excel spreadsheet tool as further described in the following sections.

Definitions of land use categories are based on FAO classification as described in section 3.7 and definitions of the production system is described in section 3.3.2.

Table 4 shows that the potential to increase the area cropland is still significant in most regions; globally some 23% of the areas mS to VS are presently under forest cover (although this is not allowed in the calculations in this study). Comparison of the total area cropland (arable land & permanent crops, IV) with the areas suitable for crop production (mS to VS) indicate that sub-Saharan Africa and Latin America have the potential to four- to six fold the area cropland. In sub-Saharan Africa this increase comes from 14% from areas currently under forest, the remaining comes mainly from pastures (mainly pastures). Latin America is the region with the largest land resources: 42% of the suitable areas cropland is currently under forest cover. In the Near East & North Africa and East Asia the potential to increase the area cropland is limited to 17% and 29% respectively, while in South Asia the total area arable land cropland is larger than the area VS to mS, indicating that crop production is currently taking place on areas classified as not suitable (NS).

*Table 4.* Comparison of agricultural land use and areas suitable for crop production. Sources: (FAO 2000b, 2002b).

| Region | Area cropland[23] based on a very high, rain-fed input system (I) 1000 ha | Areas of (I) under forest cover (II) 1000 ha | Total arable land under forest cover (III) % | Arable land & permanent crops (IV) 1000 ha | % of total area mS-VS | % of area mS-VS not under forest cover | Arable land & permanent crops & permanent pastures (V) 1000 ha | % of total area mS-VS | % of total area mS to VS not under forest cover |
|---|---|---|---|---|---|---|---|---|---|
| North America | 493 | 157 | 32 | 227 | 46 | 67 | 495 | 100 | 147 |
| Oceania | 141 | 15 | 10 | 58 | 41 | 46 | 486 | 344 | 384 |
| Japan | 12 | 4 | 30 | 5 | 42 | 59 | 6 | 45 | 65 |
| West Europe | 146 | 18 | 12 | 88 | 60 | 69 | 149 | 102 | 116 |
| East Europe | 78 | 7 | 9 | 47 | 59 | 66 | 66 | 84 | 93 |
| C.I.S. and Baltic States | 374 | 87 | 23 | 226 | 60 | 79 | 583 | 156 | 203 |
| sub-Saharan Africa | 1,025 | 144 | 14 | 169 | 16 | 19 | 986 | 96 | 112 |
| Caribbean & Latin America | 977 | 407 | 42 | 154 | 16 | 27 | 754 | 77 | 132 |
| Near East & North Africa | 122 | 3 | 3 | 101 | 83 | 85 | 459 | 377 | 388 |
| East Asia | 325 | 56 | 17 | 230 | 71 | 86 | 765 | 235 | 285 |
| South Asia | 201 | 6 | 3 | 204 | 102 | 105 | 224 | 111 | 115 |
| World | 3,894 | 904 | 23 | 1,509 | 39 | 50 | 4,971 | 128 | 166 |

Comparison of the total agricultural land use (arable land & permanent crops plus permanent pastures) with the productive area (VS to mS) indicates that the total agricultural land use is larger than the areas suitable for crop production (VS to mS)[24]. This, in many regions large areas that are classified in this study as not suitable are presently being used as pasture land. This does not necessarily mean that at this moment pasture areas are fully exploited. The technical potential to increase crop yields is further analysed in this report. Similar data on the potential to increase the quantities biomass that can be subtracted from permanent pastures were not readily available and is therefore not further analysed.

Based on the observations above, it can be concluded that in many regions, particularly the developing regions, there are considerable areas productive land presently not used as such. However, since deforestation is considered unsustainable and therefore not allowed in the scenarios included in this study, the total area agricultural land is not allowed to increase.

## 4.3 Surplus permanent pastures

In this section the future demand for permanent pastures and arable land for fodder production is analysed. As explained in section 3.4, the demand for feed from pastures and fodder is used as an *indicator* to estimate potential surpluses permanent pastures and fodder crops.

[23] Potential cropland is defined as the sum of the areas classified as VS, S, MS and mS as explained in section 3.3.2).
[24] In reality, the land use category *'other land'* may also occupy suitable cropland (see section 3.7). This means that the potential to increase the area agricultural land use is higher if these areas are available.

A decrease in demand for feed from pastures and fodder results in a corresponding decrease of the area permanent pastures and fodder crops. Any increase in the demand for feed from pastures and fodder is met by feed from crops, because:

- an increase in the demand for feed from permanent pastures and fodder crops could expansion of the area permanent pastures and cropland used for fodder crops, at the expense of forests.
- an increase in the demand for feed from permanent pastures could lead to an increase of grazing intensity, which is not allowed since this could lead to overgrazing and related environmental problems (e.g. soil erosion). There is a lack of data on this subject. Data on stocking densities, grazing intensities, pasture land productivity and the correlation with management systems do exist, but often use a different geographical breakdown than the one applied in this study and/or do not comply with the definitions used in this study (e.g. the definition of pasture pastures) and/or use a different approach (e.g. data for mature animals only, instead of data for the entire production system, including lactation etc.). There is a need for data and insight in this field, particularly with respect to pastoral animal production systems in developing regions.

The areas surplus pastureland for scenario 2 to 4 are shown in table 5.

*Table 5.* Surplus areas permanent pasture based on the demand for feed from permanent pastures and fodder crops relative to the area pastureland in 1998 (Mha).

| region | Scenario 1 &2 Mha | Scenario 3 & 4 Mha |
|---|---|---|
| North America | 92 | 322 |
| Oceania | 261 | 449 |
| Japan | 0 | 1 |
| West Europe | 31 | 78 |
| East Europe | 2 | 26 |
| C.I.S. and Baltic States | 92 | 437 |
| sub-Saharan Africa | 311 | 820 |
| Caribbean & Latin America | 395 | 613 |
| Near East & North Africa | 0 | 366 |
| East Asia | 4 | 537 |
| South Asia | 0 | 26 |
| World | 1,190 | 3,676 |

Note that due to the uncertainties related to the data used to calculate the demand for feed from permanent pastures and fodder, the data in table 5 should be considered as a rough *indicator* of the potential, rather than 'hard data'. Further, the surplus areas in table 5 provide no information on the production potential for bioenergy because:

- data on suitability for crop production are not included in table 5
- the surplus areas permanent pasture and arable land under fodder production may be used for the production of crops used for feed or food. The surplus areas are included in the Excel spreadsheet tool used to calculate the areas under crop production in 2050 (food production is given priority above bioenergy production). We decided to show the data anyhow, considering the large impact on the bioenergy production potentials.

The total demand for feed in scenarios 1 to 4 increases from 92 EJ in 1998 to 103 EJ in 2050 (based on a HHV of 19 GJ ton $dw^{-1}$). In 1998 12% of the total feed use comes from feed crops and 52% from pastures & fodder crops, the remaining demand comes from residues and scavenging. *Scenarios 3 and 4* are based on a landless (industrialised) production system. In a landless production system all animals are kept inside and all animal feed in 2050 comes from feed crops and residues. Thus, the areas permanent pasture and the areas used for fodder crop production in 1998, equal to 3.5 Gha permanent pasture and 0.2 Gha for fodder crop production (table 5), are available for the production of feed and food crops in scenario 3 and 4. For comparison: the total area arable land plus the area permanent crops in 1998 is 1.4 Gha and 0.1 Gha respectively). The data in table 5 are intermediate results, indicating the areas permanent pasture and fodder crops and without subtraction of the areas required for the production of food and feed crops in 2050.

*Scenario 1 and 2* are based on a mixed production system in which half of the animal feed required for the production of bovine meat and milk and 85% of the feed required for the production of mutton and goat meat comes from pastures. Globally, the total demand for feed from pastures and fodder decreases from 52% in 1998 to 41% of the total demand for feed in 2050. The decrease in the area permanent pasture and The remaining demand for feed is met by residues (18%) and feed crops (82%). As a result of the decreasing demand for feed from pastures and fodder crops the 1,2 Gha land used for fodder production and permanent pastures in 1998 is available for the production of feed and food crops in 2050 (table 5). The largest share of this potential comes from the Caribbean & Latin America (37%), Oceania (24%), the and sub-Saharan Africa (20%). Other regions may contribute less to the global potential, but from a regional perspective significant percentages of the area permanent pasture and arable land under fodder production in each region end up as surplus a: North America (29%), West Europe (40%) and the C.I.S. and Baltic States (21%).

The decrease in areas permanent pastures in scenario 1 and 2 is the result of the present large scale use of pastoral (grazing) production systems, which usually have lower feed conversion efficiencies than mixed production systems. In addition, in West Europe and the C.I.S. & Baltic States the total demand for animal products is projected to increase much less than in other regions or may even decrease. Note that the 1.2 Gha surplus permanent pasture and agricultural land used for fodder production, is the sum of different regions, without considering the increasing demand for feed from pastures and fodder crops in other regions. If the surplus areas permanent pastures are used to avoid the increasing demand for pasture biomass in other regions, the surplus area pasture land is limited to 0.7 Gha (globally, the demand for feed from pastures and fodder decreases 18%).

Scenarios 1 to 4 have in common that they are based on high feed conversion efficiencies and a mixed or landless animal production system. The total increase in demand for feed is limited to 12%. Scenarios based on lower feed conversion efficiencies or a pastoral production system lead to much higher demand for feed and/or feed from pastures. E.g. the demand for feed increases to 2050 by +63%, +223% and +383% based on a pastoral production system in combination with a high, intermediate and low feed conversion efficiency respectively, or increases by +106% and +201% based on a mixed production system and an intermediate and low feed conversion efficiency (*ceteris paribus*).

## 4.4 POTENTIAL TO INCREASE YIELDS

In the developing regions, the rapid increase in consumption is counteracted largely through increasing yields. According to the FAO, the projected increase in production to 2030 in the developing regions[25] is achieved for 57% by increasing yields (rain fed agriculture), 11% from

[25] The developing regions are sub-Saharan Africa, Caribbean & Latin America, Near East & North Africa, East Asia and South Asia.

increasing the cropping intensity (defined as the ratio harvested land to arable land as described in section 3.3) and 36% from increasing the area under crop production (FAO 2003b). In the industrialised and transition economies, consumption is expected to decrease slightly or increase at a much slower pace. A limited increase in yields could lead to a decrease in the area cropland as has already occurred during the last decades (section 3.3.1).

The FAO projects for the developing regions an *average* increase of cereal yields of 38% between 1998 and 2030 (FAO 2003b). However, the technical potential to increase yields above these levels is much higher as than as this study shows (even without including the impact of improvements in agricultural technology and management beyond the best available technology presently available. As described in section 3.4 the future demand for food and animal feed is translated into yield – area combinations using a Excel spreadsheet tool. The calculations include:

- the optimalisation of crop production geographically (allocation of crop production to the most suitable areas)
- the application of a intensive management system, including the use of fertilizers, pesticides and mechanisation
- the effect of technological developments other than the level of technological currently used in the industrialised regions (scenario 4 only)
- the effect or irrigation (scenario 2, 3 and 4 only).

The calculated increases in yields are shown in table 6.

*Table 6.* Average increase in crop yields per scenario (1998=1).

| Region | Scenario 1 1998=1 | Scenario 2 1998=1 | Scenario 3 1998=1 | Scenario 4 1998=1 |
|---|---|---|---|---|
| North America | 1.6 | 2.3 | 2.3 | 3.2 |
| Oceania | 2.4 | 3.7 | 3.7 | 4.6 |
| Japan | 2.7 | 2.8 | 2.4 | 3.0 |
| West Europe | 0.9 | 1.5 | 1.3 | 1.9 |
| East Europe | 2.1 | 3.3 | 3.3 | 4.1 |
| C.I.S. and Baltic States | 3.2 | 5.4 | 5.3 | 6.7 |
| sub-Saharan Africa | 5.6 | 6.2 | 6.2 | 7.7 |
| Caribbean & Latin America | 2.8 | 3.6 | 3.5 | 4.5 |
| Near East & North Africa | 1.4 | 2.3 | 2.3 | 2.9 |
| East Asia | 2.3 | 2.7 | 2.5 | 3.2 |
| South Asia | 3.7 | 4.5 | 4.5 | 5.6 |
| World | 2.9 | 3.6 | 3.6 | 4.6 |

Table 6 shows that the maximum increase in yields (scenario 4) is considerable: globally a factor 4.6 with regional variation between 1.9 in West Europe to 7.7 in sub-Saharan Africa. Based on existing technologies common in the industrialised regions, yields are projected to increase by a factor 3.6 globally, with regional variation between 1.3-1.5 in West Europe to 6.2 in sub-Saharan Africa (scenario 2 and 3). The lower yields in scenario 3 compared to scenario 2 are the result of the high demand for crops used for feed in scenario 3, which requires the use of less productive areas and results in slightly lower yield increases. In scenario 1 the potential yield increase is 2,9, compared to 3.6 in scenario 2, because scenario 2 includes irrigation and scenario 1 is based on rain-fed agriculture only. Regionally, the effect of irrigation on the potential yield increases is much larger: CIS & Baltic States (from a potential yield increase factor of 5.4 to 3.2), Oceania (from a potential yield increase factor of 3.7 to 2.4) and the Near East & North Africa (from 2.3 to 1.4).

## 4.5 SURPLUS AGRICULTURAL AREA

As described in the previous section, the potential to increase yields above the levels achieved today or projected for 2030 is considerable in all regions. If the projected yield levels are actually realised, the total area agricultural land required for food production may decrease theoretically, freeing productive land for bioenergy production. Table 7 shows the areas 'superfluous' agricultural land in 2050 in the scenario 1 to 4. The data in table 7 includes any surplus areas permanent pasture an arable land used for fodder production and the regional data include the demand for food or feed crops from other regions (the self-sufficiency of the world as a hole is 100%).

*Table 7.* Area surplus agricultural land in 2050 including permanent pastures and arable land for fodder production. The three columns given for each scenario indicate the surplus area in Mha, the percentage of the total agricultural area in 1998 and the self-sufficiency ratio of each region (% SSR).

| Region | Scenario 1 | | | Scenario 2 | | | Scenario 3 | | | Scenario 4 | | | Total agric. area |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mha | Area (%) | SSR (%) | Mha | Area (%) | SSR (%) | Mha | Area (%) | SSR (%) | Mha | Area (%) | SSR (%) | Mha |
| North America | 54 | 10 | 97 | 105 | 19 | 100 | 307 | 56 | 100 | 348 | 64 | 100 | 547 |
| Oceania | 216 | 42 | 100 | 236 | 46 | 100 | 405 | 80 | 100 | 428 | 84 | 100 | 509 |
| Japan | 0 | 0 | 30 | 0 | 0 | 30 | 0 | 0 | 46 | 0 | 0 | 54 | 6 |
| West Europe | 12 | 7 | 86 | 22 | 13 | 100 | 38 | 23 | 97 | 61 | 37 | 100 | 165 |
| East Europe | 4 | 6 | 99 | 16 | 22 | 100 | 35 | 49 | 100 | 40 | 56 | 100 | 72 |
| C.I.S. and Baltic States | 113 | 17 | 97 | 153 | 23 | 98 | 470 | 72 | 99 | 491 | 75 | 99 | 653 |
| sub-Saharan Africa | 104 | 10 | 98 | 240 | 24 | 98 | 619 | 62 | 99 | 717 | 72 | 99 | 992 |
| Caribbean & Latin America | 152 | 20 | 98 | 310 | 40 | 99 | 500 | 65 | 98 | 555 | 72 | 99 | 772 |
| Near East & North Africa | 23 | 5 | 20 | 11 | 2 | 57 | 372 | 80 | 50 | 372 | 80 | 60 | 463 |
| East Asia | 15 | 2 | 36 | 23 | 3 | 38 | 509 | 66 | 37 | 510 | 66 | 45 | 767 |
| South Asia | 36 | 16 | 40 | 38 | 16 | 54 | 57 | 25 | 47 | 63 | 27 | 54 | 231 |
| World | 729 | 14 | 99 | 1,153 | 22 | 100 | 3,313 | 64 | 100 | 3,586 | 70 | 100 | 5,143 |

Globally, the self-sufficiency is 100% in all four scenarios. Thus, the data in table 7 indicate that the world can be self-sufficient in 2050 and simultaneously reduce the area agricultural land without decreasing the area land under forest cover. In case the SSR of a region is below 100%, the shortage of food is allocated to other regions. The SSR's are shown to indicate to what extend region is capable of producing the domestic demand for food and feed. Globally, the agricultural area required for food production may decrease by 14%, 22%, 64% and 70% in scenario 1 to 4.

The regions with the largest (potential) surplus cropland are the Caribbean & Latin America and sub-Saharan Africa. Both regions can be fully self-sufficient. The Caribbean & Latin America has a potential surplus land of 0.2 Gha in scenario 1 up to 0.6 Gha in scenario 4, equal to 20% to 72% of the total agricultural area in 1998. Sub-Saharan Africa has a potential surplus land of 0.1 Gha in scenario 1 up to 0.7 Gha in scenario 4, equal to 10% to 72% of the agricultural area in 1998. The large potential originates mainly from the large areas surplus pastureland presently used (table 4).

The Near East & North Africa, South Asia and partially East Asia are land stressed regions with self-sufficiency ratios (SSR) well below 100%. The SSR's in these regions is 55%, 58% and 43% respectively based on irrigated agriculture and 20%, 43% and 38% is only rain-fed agriculture is applied. The remaining demand for food is imported from other regions. However, as can be seen in table 7, East Asia, South Asia and Near East & North Africa still have a considerable potential to produce bioenergy on surplus arable land, despite the low SSR's, particularly in scenario 3 and 4. This potential results from:

- areas that are classified as not suitable for crop production. Not suitable areas are areas with yields less than 20% of the maximum constraint free yield. Data on the productivity of these areas for food crops were not available. However, the dataset used to calculate the potential for bioenergy production includes data on yields for NS areas. This also indicates that crop growth may be possible on these areas (as is also shown in table 4 crop production takes place in South Asia on areas classified as not suitable.
- a mismatch between the demand indicated by the model and the potential for crop production. A surplus of the total area suitable for crop production and a surplus of the areas suitable for production of various crops is possible due to a lack of remaining demand for these crops and despite a shortage of production potential for other crops. E.g. in South Asia the production potential for wheat is insufficient to meet the projected demand (the shortage is included in the demand in other regions), while at the same time South Asia has a surplus production potential for sorghum. This situation is partially caused by the fact that the allocation procedure (calculation of yield-area combinations) does not always lead to a minimalisation of the arable land use or optimalisation of the SSR.

The remaining demand for food in the East Asia, South Asia and Near East & North Africa is allocated to regions with a remaining production potential of the crops of which there is a shortage. This limits the potential of bioenergy in sub-Saharan Africa, the Caribbean & Latin America and other regions with a surplus of food production potential. E.g. without this effect, the surplus areas agricultural land in sub-Saharan Africa and the Caribbean & Latin America would increase from 310 to 396 Mha and from 240 Mha to 346 Mha respectively (scenario 2).

These observations are in line with other reports that indicate land shortages in South Asia, the Near East & North Africa and East Asia (e.g. (FAO 2003b). The data in table 6 and 7 match land potential profiles outlined in table 4: high potentials in sub-Saharan Africa and the Caribbean & Latin America, limited land potential in East Asia and land shortages in South Asia and Near East & North Africa.

The CIS & Baltic States has a considerable potential of 0.1 Gha (scenario 1) up to 0.5 Gha (scenario 3 and 4), equal to one-fifth to three-third of the total agricultural land use. The potential in East Europe measured in Mha ranges between 4 to 40 Mha, equal to one-twentieth to half of the total area agricultural land use.

With the exception of Japan, the industrialised regions are nearly or fully self-sufficient in all four scenarios. Japan is clearly the most land stressed region with a self-sufficiency ratio of e.g. 30% in scenario 1 and 2. Oceania has the largest potential to increase yields and reduce the area agricultural land. Even if an intermediate feed conversion efficiency and intermediate level of agricultural technology is used, Oceania can be fully self-sufficient and free some 30 Mha for bioenergy production (data not shown). Based on scenario 1 to 4, between 42% to 84% of the total agricultural land use in 1998 can be abandoned for bioenergy production. North America also has the potential to reduce the area agricultural land significantly, between 54 Mha to 348 Mha, equal to 10% to 64% of the agricultural area in 1998. The high potentials of both regions are the result of:

- the impact of irrigation (see also table 6) and
- the large areas suitable land currently used for other purposes than crop production, mainly pasture areas (table 4).

Note that the areas shown in table 6 provide little information on the potential to grow bioenergy crops, because data on productivity are not included.

### 4.6 Bioenergy production from abandoned agricultural land

The total areas surplus agricultural land (arable land plus permanent pastures) available for bioenergy production in the four scenario is shown in table 7. The data however do not indicate the productivity of these areas. Figure 10 shows the areas surplus agricultural land, classified as very suitable (VS), suitable (S), moderately suitable (MS), marginally suitable (mS) and not suitable (NS).

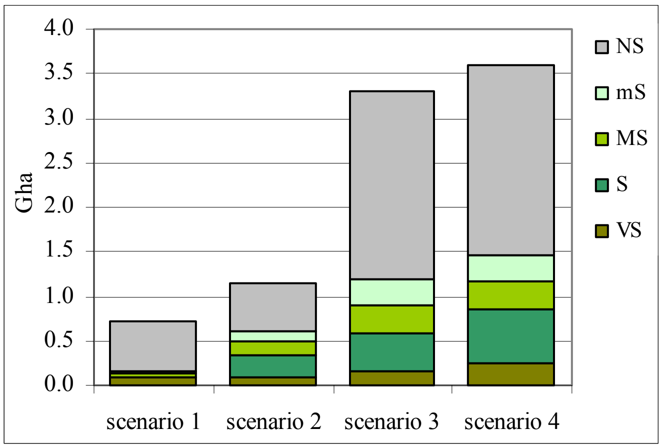



*Figure 10.* Areas abandoned agricultural land (cropland and permanent pasture ) in 2050 (Gha).

The results indicate that considerable areas can be made available for bioenergy production 0.7 Gha, 1.2 Gha, 3.3 Gha and 3.6 Gha in scenario 1, 2, 3 and 4 respectively. The difference between the scenarios is considerable, indicating the large impact of the animal production system, particularly the impact of a landless production system (scenario 3). The calculations of the potential to grow woody bioenergy crops takes into account the productivity of the surplus areas and specific yields on these areas, shown in figure 9. Table 8 shows the regional bioenergy production potentials (based on a higher heating value of 19 GJ/ton dw).

In all scenarios, the largest potential comes from the developing regions Sub-Saharan Africa, the Caribbean & Latin America and East Asia. The potential in Sub-Saharan Africa and the Caribbean & Latin America results from the present very inefficient production systems and inefficient land use patterns (large areas permanent pasture) and low cropping intensity (63% and 68%). For East Asia the potential is also the result of mismatch between demand and supply. After the first 24 allocation steps in which no trade is included, East Asia has a SSR of 38% to 51% in scenario 1 to 4. The potential for bioenergy production indicated in table 8 results from areas suitable for crops for which there is no domestic demand or areas not suitable for the production of food, but suitable for bioenergy crop production.

*Table 8.* Regional bioenergy production potentials ($EJy^{-1}$) in 2050 based on surplus agricultural land (arable land and permanent pastures).

| Region | Scenario 1 $EJy^{-1}$ | Scenario 2 $EJy^{-1}$ | Scenario 3 $EJy^{-1}$ | Scenario 4 $EJy^{-1}$ |
|---|---|---|---|---|
| North America | 20 | 53 | 144 | 174 |
| Oceania | 38 | 51 | 87 | 102 |
| Japan | 0 | 0 | 0 | 0 |
| West Europe | 5 | 11 | 16 | 30 |
| East Europe | 3 | 11 | 22 | 26 |
| C.I.S. and Baltic States | 45 | 73 | 184 | 199 |
| sub-Saharan Africa | 31 | 102 | 260 | 317 |
| Caribbean & Latin America | 47 | 120 | 190 | 221 |
| Near East & North Africa | 2 | 1 | 30 | 31 |
| East Asia | 11 | 17 | 146 | 147 |
| South Asia | 15 | 17 | 21 | 25 |
| World | 215 | 455 | 1,101 | 1,272 |

The origin of the potential from the C.I.S. & Baltic States results from a combination of limited increase in population growth, limited increase in consumption (compared to the developing regions) and large areas agricultural land resulting from the communistic era when consumption was considerably higher (figure 3 and 4). The potential of the industrialised countries is particularly present in Oceania and partially also in North America and West Europe. According to the calculations, the land stressed regions Japan, South Asia, Near East & North Africa are all regions that have a limited potential. This potential originates mainly from areas classified as not suitable for the production of food and feed, but suitable for the production of bioenergy. These areas were previously permanent pastures.

## 4.7 BIOENERGY PRODUCTION FROM NATURAL FOREST GROWTH

Figure 11 shows the global demand and (potential) supply of fuelwood and industrial roundwood in 2050 in EJ. Three demand scenarios are included based on the range of demand projections found in literature (low, medium and high) based on a literature search. Three supply scenarios are based on natural forest growth (one scenario) and three plantation scenarios (low, medium and high). The difference between demand and supply indicates a theoretical shortage. Further details of the scenarios on demand, natural forest growth and plantations are described in the sections 3.5 and Appendixes F, G and J. The use of standing stocks through selective removal of trees or deforestation is not included in this analysis since such practices are considered unsustainable, although the potential is very large (roughly 90 times the current wood consumption). Appendix S gives an overview of the volumes standing forest stocks and current deforestation rates to indicate the magnitude.

The data show that (theoretically) the world is capable of producing enough roundwood to meet demand from forests without the use of standing stocks or deforestation. Trade is considered to become more important to meet the demand in forest resource poor regions such as Japan, the Near East & North Africa, South Asia. Plantations are likely to become important sources of wood, up to half of the total wood demand in 2050. The remainder of the demand will have to be supplied from natural forest growth.

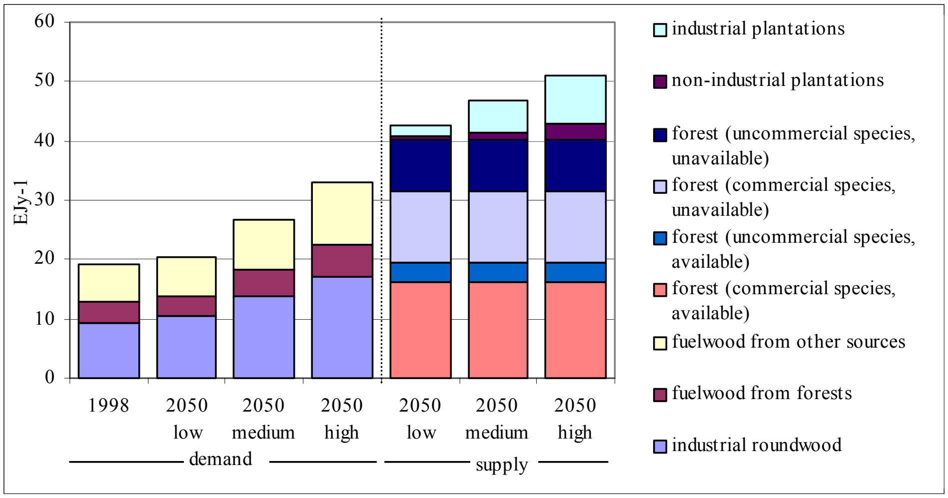



*Figure 11.* Roundwood demand and supply in 2050 assuming no deforestation (un)c.s. = uncommercial species, (un)av.= unavailable[26]. Sources: (FAO 1998b, 2001, 2002a), own calculations.

The total (technical) surpluses of annual forest growth is 29 $EJy^{-1}$ (medium demand scenario and medium plantation establishment scenario), with a range of 20 to 38 $EJy^{-1}$ dependent on the combination of demand and supply scenarios (note that data on forest growth are very scarce and uncertain). In reality, the supply of wood from natural forests may be limited by various factors:

- Roughly half of the global forest areas forest area is old-growth undisturbed forest. For reasons of nature protection these areas may be excluded from supply. Globally, roughly half of the forest area is disturbed, with large regional differences: 3% of the forest area is disturbed in the C.I.S. & Baltic States, 42% in Latin America, 71% in North America and 100% in West and East Europe. if undisturbed forest areas are excluded from production, the surplus bioenergy production potential decreases from 33 to 8 $EJy^{-1}$ (medium consumption and plantation scenario).
- Some two third of the annual forest growth consists of species that are presently commercially harvestable (commercial species). For the remaining production, there is presently no market. The C.I.S. & the Baltic States, North America and West Europe are the regions with the high forest growth of uncommercial species (see Appendix N). If the use of wood from natural forest growth is limited to commercial species, the bioenergy potential decreases from 29 to 5 $EJy^{-1}$.
- Not all forest areas are available for wood production. If the production of roundwood is limited to available areas only, the surplus bioenergy production decreases to 1 $EJy^{-1}$.

If all restriction are combined, the wood demand in 2050 can not be met. However, the three restriction may partially overlap, so the actual shortage is likely less, but difficult to estimate.

## 4.8 BIOENERGY PRODUCTION FROM RESIDUES

The bioenergy potential from residues from forestry and agriculture and wastes are calculated as described in section 3.9. Contrary to the bioenergy production potential from bioenergy crops on surplus agricultural areas, the bioenergy potential from is not related to the issue of food security, except for the use of residues in the animal food production system. Therefore, data on the

[26] Unavailable areas are defined as:
- Physically inaccessible areas due to factors such as steepness of terrain
- Areas far from industrial sites due to transportation distances or lack of infrastructure
- Areas too low in commercial volume, degraded forest or some other legitimate reason specific to each country.

potential of residues also include scenarios in which the projected demand for food in 2050 can not be produced.

Table 9 shows the production and use of agricultural and forestry residues in 2050. The production of agricultural (crop) residues is based on the regional *production* of food multiplied by harvesting or processing factors and the recoverability factor (section 3.9).

*Table 9.* Production of agricultural residues in 2050 ($EJy^{-1}$).

| Region | Harvesting residues production $EJy^{-1}$ | | | | Processing residues $EJy^{-1}$ | Use of residues for feed $EJy^{-1}$ | Logging residues $EJy^{-1}$ | Sum of all residues $EJy^{-1}$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Scenario | | | | Scenario | Scenario | Scenario | Scenario | | | |
| | 1 | 2 | 3 | 4 | 1,2,3,4 | 1,2,3,4 | medium | 1 | 2 | 3 | 4 |
| North America | 5 | 8 | 10 | 10 | 1 | 2 | 3 | 7 | 10 | 12 | 12 |
| Oceania | 2 | 4 | 5 | 4 | 0 | 0 | 0 | 2 | 4 | 5 | 4 |
| Japan | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| West Europe | 2 | 2 | 3 | 4 | 1 | 2 | 2 | 3 | 3 | 4 | 5 |
| East Europe | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| C.I.S. and Baltic States | 3 | 3 | 4 | 4 | 0 | 1 | 1 | 3 | 3 | 4 | 4 |
| sub-Saharan Africa | 15 | 12 | 20 | 18 | 2 | 2 | 0 | 15 | 12 | 20 | 18 |
| Caribbean & Latin America | 11 | 10 | 12 | 11 | 2 | 3 | 1 | 11 | 10 | 12 | 11 |
| Near East & North Africa | 1 | 2 | 2 | 3 | 1 | 2 | 0 | 0 | 1 | 1 | 2 |
| East Asia | 4 | 4 | 5 | 6 | 4 | 5 | 1 | 4 | 4 | 5 | 6 |
| South Asia | 5 | 6 | 7 | 8 | 4 | 2 | 0 | 7 | 8 | 9 | 10 |
| World | 52 | 52 | 69 | 69 | 16 | 19 | 9 | 58 | 58 | 75 | 75 |

Table 9 shows that (theoretically) the production of the crop harvest residues and processing residues is sufficient to meet the demand for residues for feed. In total, some 55 $EJy^{-1}$ to 72 $EJy^{-1}$ are available for bioenergy production in 2050.

The produced amounts of harvesting residues increase with a decreasing level of technology. In general, in technologically advanced production systems crop species are used with higher harvest indexes than in less technologically advanced production systems (see further section 3.9 and Appendix R). Scenario 1,2,3 and 4 are all based on high input system. If e.g. an agricultural production system with intermediate and low inputs is used, the production of harvest residues increases 40% and 117% respectively (data not shown). A limiting factor for the availability of residues is that residues are often already used as fuel, animal bedding, soil improver or as a source of fibre for the paper industry. Further, there are various other sources of residues not included in this study due to lack of detailed data and because the bioenergy potential of these sources is indicated below. Other potential sources are e.g.:

- organic urban waste. The potential of organic urban waste is estimated at 1 to 3 $EJy^{-1}$in 2050 (Hoogwijk 2002). Data on household losses are limited, but from a study on losses in American households it can be concluded that 27% is lost or discarded (Kantor *et al.* 1997). Data from Japan indicate a comparable amount of losses of 22 % (Fujino *et al.* 1999). Considering a production of food in 2050 of 67 $EJy^{-1}$, the total production of organic waste is likely significantly higher (17 $EJy^{-1}$ based on a 25% recoverability).
- dung. The average production of dung in 1992-1995 is estimated at 46 $EJy^{-1}$ (Wirsenius 2000) of which 12,5 to 25% is estimated to be recoverable for energy production, equal to 6 $EJy^{-1}$ to 12 $EJy^{-1}$. Based on the projected increase of the number of animal in the SRES scenarios included in the IMAGE model, this potential increases to 9 $EJy^{-1}$ to 19 $EJy^{-1}$

(Hoogwijk 2004). Other studies estimated the potential of manure at 100 $EJyr^{-1}$ of which some one fourth is recoverable (Johanssen *et al.* 1993) and 13 $EJy^{-1}$ (Williams, 1995 in Hoogwijk, 2004).

## 4.9 BIOMASS EXPORTING POTENTIAL

If the use of modern bioenergy is going to increase rapidly as some global energy scenarios indicate, than an entirely new (global) market for bioenergy will emerge. As with any commodity, trade will take place to match supply and demand between regions with surpluses or shortages bioenergy. In such a global bioenergy market, the export of biomass of a certain region at the expense of the domestic bioenergy supply is unwanted since this does not lead to a net increase in the share of bioenergy in the global energy mix. Therefore, the ratio between the bioenergy production potential and the energy demand can be used as an indicator to estimate the surplus (regardless of how much of this biomass is actually being used). Table 10 shows the bioenergy potential relative to three scenarios for total primary energy consumption. The scenarios are based on the relative annual increase in energy consumption based on scenarios from the WEC/IIASA study Global Energy Perspectives (WEC 1998b). The total energy use in 2050 in the high, medium and low consumption scenario is 1041 EJ, 837 EJ and 601 EJ respectively. Further scenario details are described in Appendix S.

*Table 10.* Ratio domestic energy demand and domestic bioenergy production potential in 2050.

| | Scenario 1 | | | Scenario 2 | | | Scenario 3 | | | Scenario 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | low | medium | high | low | medium | high | low | medium | high | low | medium | high |
| North America | 0.2 | 0.2 | 0.4 | 0.4 | 0.4 | 0.9 | 0.9 | 1.1 | 2.2 | 1.0 | 1.2 | 2.4 |
| Oceania | 4.9 | 6.6 | 9.8 | 6.8 | 9.2 | 13.6 | 11.5 | 15.4 | 22.8 | 12.7 | 17.1 | 25.3 |
| Japan | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| West Europe | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | 0.3 | 0.4 | 0.3 | 0.4 | 0.5 |
| East Europe | 0.2 | 0.2 | 0.3 | 0.5 | 0.6 | 0.9 | 1.0 | 1.2 | 1.8 | 1.1 | 1.3 | 2.0 |
| C.I.S. and Baltic States | 0.5 | 0.6 | 1.2 | 0.8 | 1.0 | 1.9 | 1.9 | 2.5 | 4.6 | 2.0 | 2.7 | 4.9 |
| sub-Saharan Africa | 0.6 | 0.8 | 0.9 | 1.6 | 2.1 | 2.3 | 3.8 | 5.0 | 5.5 | 4.4 | 5.7 | 6.3 |
| Caribbean & Latin America | 0.8 | 0.9 | 1.2 | 1.8 | 2.1 | 2.7 | 2.8 | 3.2 | 4.2 | 3.1 | 3.5 | 4.6 |
| Near East & North Africa | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.4 | 0.5 | 0.3 | 0.4 | 0.4 |
| East Asia | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.6 | 0.7 | 1.0 | 0.6 | 0.7 | 1.0 |
| South Asia | 0.2 | 0.3 | 0.3 | 0.2 | 0.3 | 0.3 | 0.3 | 0.4 | 0.4 | 0.2 | 0.3 | 0.3 |
| World | 0.3 | 0.3 | 0.5 | 0.5 | 0.6 | 0.9 | 1.1 | 1.4 | 2.0 | 1.2 | 1.5 | 2.1 |

The region with the largest ratio between the domestic production capacity of bioenergy and domestic energy demand is Oceania, up to a factor 26. The transition countries and sub-Saharan Africa also have considerable bioenergy production potential (and export surpluses). Globally, the bioenergy potential is sufficiently large enough to meet the global bioenergy demand in 2050 by some 30% to 210%.

# 5. SENSITIVITY ANALYSIS

The effect of different factors on the potential of a region to produce bioenergy is analysed in this study through various scenarios. The effect of the animal production system (pastoral, mixed or landless ), the efficiency of feed conversion and the crop production system are key factors for the bioenergy production potentials. In section 5.1 the impact of the methodology used is analysed. In section 5.2 the impact of various other parameters than included in the scenarios is analysed.

Obviously, there are numerous more factors that may influence the bioenergy production potentials. To name a few of the most important parameters: globalization and trade policies, soil degradation, agricultural and environmental policies, recycling ratios, income, biotechnology, climate change. We did not include these aspects specifically, due to a lack of data and time and because the focus on this study is on the *technological* potential instead of a *most-likely* scenario or an *economic* potential. However, some of the factors mentioned above are included in the consumption scenarios (e.g. growth of GDP is included in the scenario for the consumption for food). For an discussion on these and other issues and the impact on agriculture during the coming 30 years, we refer to the FAO report Agriculture towards 2015/2030 (FAO 2003b).

## 5.1 METHODOLOGICAL ISSUES

In the Excel spreadsheet tool the production potential for different crops is limited by the total land available and suitable for crop production and the crop specific areas. The total area suitable and available for crop production is used as a measure for the overlap between the areas suitable for the different crops included in the model (the sum of crop specific areas may not exceed the total area available for crop production). This method may overestimate the production potential, if in reality in the suitable areas for different crops are located within a certain area of the total area suitable for crop production (with the exception of one crop since the total areas suitable for crop production is defined as the area where at least one crop may grow, section 3.3 and Appendix H). The production potential is only overestimated if there is no or limited demand for the latter crop type. The possibility of an overestimation of the production potential can be reduced if the total area cropland is based on the three most important cereals (wheat, maize, rice) only, instead of all crops. As a result the total area suitable and available for crop production decreases. The decrease of the total bioenergy production potential is below 14% in all four scenarios.

Further, a more intensive production system not necessarily leads to increase of the area surplus area cropland. E.g. the area surplus agricultural land in the C.I.S & Baltic States decreases from 366 million hectares in a very high rain-fed production system, compared to 340 million hectares in a very high rain-fed/irrigated production system. This decrease is the result of:

- Differences in allocation inherent to the allocated procedures used to calculate the yield area combinations. E.g. a management system with higher inputs allows an increase in the allocation of oilcrops at the expense of cereals (each of allocation step is based on the dry weight of the demand compared to the total dry weight demand). The result is a decreasing surplus area cropland due to the higher dry weight production per hectare of cereals compared to oilcrops.
- Differences in the land suitability profile. A high(er) input systems is capable of producing higher yields. However, the areas suitable for crop production may decrease, because the classification Very Suitable (VS), Suitable (S), Moderately Suitable (MS), Marginally Suitable (mS) and Not Suitable (NS) is based on *percentage* of the maximum constraint free

yield (MCFY) achievable in a region and not the *absolute* yield levels. The MCFY increases with higher levels of technology. If in a certain area yields are limited by natural circumstances the production system is unable to compensate for, that area may be classified as NS compared to mS in a production system based on a higher level of technology. Since mS areas are included in the allocation procedure and NS areas are not, the total production potential may decrease (section 3.3.2 and Appendix H). Consequently, the allocation procedure used to allocate the demand for crops to yield-area combinations included in the Excel spreadsheet tool leads to an underestimation of the bioenergy production potentials in a high production system.

The Excel spreadsheet tool used to calculate the areas surplus agricultural land (classified as NS to VS) uses input data about the areas NS to VS available for food production. The areas available for food production are based on a set of allocation rules as described in section 3.7. The allocation of the areas NS to VS to different land use categories inevitably introduces errors, partially because the areas suitable for crop production are relatively small compared to the various land use classes allocated. E.g. *'permanent pastures'* occupy in total 3.6 Gha globally and the total global area suitable cropland is 3.8 Gha. The use of georeferenced data (data that include information on geographic location e.g. maps) on present land use and the suitability would be ideal. However, this approach is considered too complex taking into account the limited time and resources available for this study and also because maps are only available for a limited number of datasets. A limited shift of 10% of the areas available and suitable for crop production (sum of very suitable, suitable, moderately suitable and marginally suitable areas) results in a decrease of the potential to produce bioenergy by 17% in scenario 2 and ca. 10% in scenario 1, 3 and 4 (the area NS increases to compensates for the decrease).

## 5.2 IMPACT OF DIFFERENT MODEL PARAMETERS

The potential of a region to produce bioenergy is influenced by numerous factors. Some of these factors are specifically included in the calculations, others are quantitatively included in the discussion and some are left our or are incorporated in more aggregated parameters. Based on the literature analysis, we found that many if not most factors come with considerable uncertainties resulting in large ranges. The combination of the ranges and uncertainties of different factors result in a very large number of parameter combinations and a meaningless large range of bioenergy production potentials if modelled linearly. Especially the impact of differences in *annual* growth rates over a fifty year period and differences in elasticities result in large ranges. In reality, the entire *socio-economic system* includes many feed back mechanisms which are poorly understood. Not surprisingly that many studies bare based on a considerable amount of *expert judgement.* We analyse the impact on the bioenergy production potential by varying one or two of the most important factors at a time. This analysis is limited to the most important parameters only, various underlying parameters (e.g. GDP) are excluded or are debated in the sections on methodologies and the Appendixes.

The combined effect of the three scenarios for *population growth* and the three scenarios for the *per capita consumption* results in a large range of demand for food. Table 11 shows the demand in total demand for food in scenario 1,2,3,4 (medium population growth and medium increase in per capita intake), a scenario based on low population growth and low per capita demand and a scenario based on high population growth and high per capita demand. The data are meant to show the *impact* of population growth and the per capita consumption on the total demand for food and the data can be used as an indicator for the *probability* of the bioenergy production potentials of scenario 1 to 4. E.g. a large range in population growth indicates a considerable uncertainty, a small range indicates the opposite.

*Table 11.* Impact of different scenarios for per capita consumption and population growth to 2050 on the total demand for food. POP = population; P.C.C. = per capita consumption; TOT = total demand for food. Sources: (IFPRI 2001a; IMAGE-team 2001; UNPD 2002; FAO 2003b), own calculations.

| Region | Scenario 1,2,3,4 1998=1 | | | Low food demand 1998=1 | | | High food demand 1998=1 | | | Low food demand $EJy^{-1}$ | Medium feed demand $EJy^{-1}$ | High food demand $EJy^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | POP | P.C.C. | TOT | POP | P.C.C. | TOT | POP | P.C.C. | TOT | | | |
| North America | 1.47 | 1.04 | 1.53 | 1.28 | 1.04 | 1.34 | 1.68 | 1.04 | 1.75 | 55 | 53 | 49 |
| Oceania | 1.35 | 1.11 | 1.49 | 1.21 | 1.08 | 1.32 | 1.5 | 1.13 | 1.69 | 55 | 51 | 41 |
| Japan | 0.87 | 1.13 | 0.99 | 0.8 | 1.12 | 0.89 | 0.95 | 1.15 | 1.09 | 0 | 0 | 0 |
| West Europe | 0.98 | 1.07 | 1.05 | 0.88 | 1.06 | 0.93 | 1.1 | 1.08 | 1.19 | 10 | 11 | 11 |
| East Europe | 0.84 | 1.14 | 0.95 | 0.75 | 1.12 | 0.83 | 0.93 | 1.16 | 1.08 | 13 | 11 | 9 |
| C.I.S. and Baltic States | 0.83 | 1.2 | 1,00 | 0.72 | 1.16 | 0.83 | 0.96 | 1.25 | 1.20 | 87 | 73 | 57 |
| sub-Saharan Africa | 2.55 | 1.32 | 3.36 | 2.15 | 1.25 | 2.68 | 2.99 | 1.39 | 4.15 | 123 | 102 | 78 |
| Caribbean & Latin America | 1.53 | 1.22 | 1.87 | 1.24 | 1.17 | 1.46 | 1.84 | 1.27 | 2.35 | 132 | 120 | 103 |
| Near East & North Africa | 2.05 | 1.15 | 2.35 | 1.7 | 1.11 | 1.88 | 2.44 | 1.19 | 2.90 | 1 | 1 | 1 |
| East Asia | 1.22 | 1.16 | 1.42 | 0.99 | 1.12 | 1.12 | 1.49 | 1.20 | 1.79 | 17 | 17 | 16 |
| South Asia | 1.70 | 1.35 | 2.29 | 1.39 | 1.28 | 1.78 | 2.06 | 1.39 | 2.87 | 18 | 17 | 16 |
| World | 1.50 | 1.19 | 1.79 | 1.25 | 1.15 | 1.43 | 1.79 | 1.23 | 2.20 | 511 | 455 | 380 |

The total global increase in food intake between 1998-2050 is +79% in the medium scenario, compared to +43% and +120% in the low and high scenario respectively. The bioenergy production potential from bioenergy crops decreases by 16% in the high food consumption scenario and the bioenergy production potential increases by 12% in the low food consumption scenario. As can be seen in table 11, the largest contribution to the range in food demand in the low, medium and high scenario comes from population growth.

In the calculations the high *plantation* establishment scenario is included (both industrial and non-industrial) to avoid overestimation of the bioenergy production potentials. In case of a low and medium plantation establishment, the bioenergy production potential increases by 24%, 19%, 8% and 7% respectively.

# 6. DISCUSSION AND CONCLUSIONS

In this a methodology to estimate bioenergy potentials in 2050 is developed. The total potential for bioenergy production (bioenergy from bioenergy crops, agricultural residues) is shown in figure 12.


*Figure 12.* Total bioenergy production potential in 2050 in scenarios 1 to 4 (EJy$^{-1}$; the left bars is scenario 1, the right bar is scenario 4).

The results clearly indicate that the *technical* potential to increase crop yields and increase the efficiency of the animal production system are large enough to compensate for the increase in food demand to 2050. The total global bioenergy production potential in 2050 in the four scenarios is 273 EJy$^{-1}$, 513 EJy$^{-1}$, 1176 EJy$^{-1}$ and 1471 EJy$^{-1}$ for scenario 1,2,3 and 4 respectively. Harvest and processing residues account for 58 EJy$^{-1}$ (scenario 1 and 2) to 75 EJy$^{-1}$ (scenario 3 and 4) of this potential, the remaining potential comes from specialised bioenergy crops on surplus agricultural areas. The increase in the contribution of harvest and processing residues is the result of differences in demand for feed crops. The surplus production potential of wood from natural forests is estimated at 20 to 36 EJy$^{-1}$, although various limiting factors, such as the exclusion of undisturbed forest may reduce this potential to 0 EJy$^{-1}$.

The results are in line with various other estimates of the bioenergy production potential. E.g. according to a recent study on the bioenergy production potentials in the SRES scenarios based on the IMAGE model, the global potential is 311 EJy$^{-1}$ in the A2 scenario, 324 EJy$^{-1}$ in the B2 scenario, 659 EJy$^{-1}$ in the A1 scenario to 706 EJy$^{-1}$ in the B1 scenario in 2050 (Hoogwijk *et al.* 2003). A comparison of various bioenergy potential assessments reveals that the potential for bioenergy varies globally between 40 and 1100 EJy$^{-1}$ with the bulk between 200 and 700 EJy$^{-1}$ (Hoogwijk 2002). Comparison is however very difficult since most due to differences in the goal and methodology used to estimate the potential.

The most promising regions for the large scale supply of bioenergy are:

- sub-Saharan Africa, the Caribbean & Latin America and East Asia. These three regions account for more than half of the global potential. In sub-Saharan Africa and the Caribbean & Latin America the potential originates from the large areas land suitable for crop production, despite the projected increase in population and consumption to 2050. The land balance in East Asia is less favourable, but the growth in population and consumption is limited in combination with large areas . A prerequisite for the bioenergy potential in all regions is however, that the present inefficient and low-intensive agricultural management systems are replaced in 2050 by the best practice agricultural management systems and technologies. In addition, per capita food consumption projected for 2050 in these regions has not reached saturation levels. Thus, the potential to may be limited if food intake (income) increases more than projected in this study.

- North America and Oceania. Despite the high levels of food consumption and the projected increase in population in these regions over the next 50 years, optimalisation of land use patterns and agricultural management results in a considerable reduction of the land required for crop production.
- C.I.S. & Baltic States. The potential of the C.I.S. & Baltic States to produce bioenergy results from a combination of drivers. Due to the collapse of communism and the economic restructuring afterwards, GDP and consumption have decreased, resulting is a decrease of yields and production. It will take several decades before consumption levels are back to levels common in the Soviet period. In addition, the population is projected to decrease to 2050. Consequently, the agricultural land area is relatively large compared to the projected demand for food, which makes the potential of this regions the most robust of all regions.

The methodology to estimate bioenergy production potentials can also be used at a more regional level and per crop type, although the methodology and data are somewhat crude for this level of detail. Box 2 shows an example the Ukraine.

**Box 2. Case study: the potential for bioenergy production in the Ukraine.**

The Ukraine is a promising regions for the production of bioenergy for various reasons:

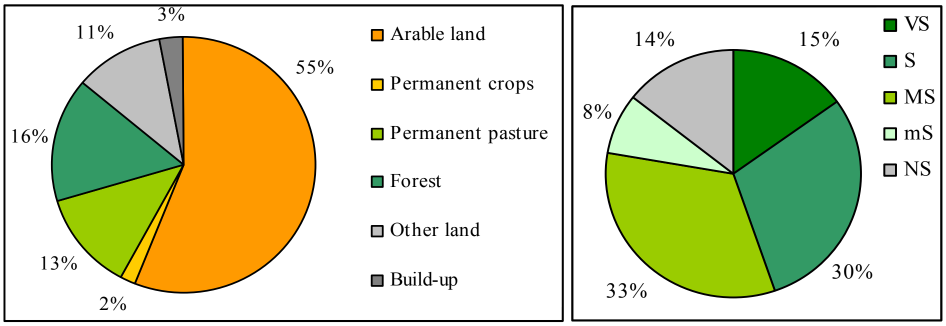
- Consumption levels have decreased since the fall of communism, particularly in the Ukraine. Daily average food intake expressed in kcal $cap^{-1}$ $day^{-1}$ decreased from 3362 kcal in 1992 to 2773 kcal $cap^{-1}$ $day^{-1}$ in 1996 and increased again to 3008 kcal $cap^{-1}$ $day^{-1}$ in 2001 (FAO 2002a). Particularly the consumption of meat decreased rapidly, from 288 kcal $cap^{-1}$ $day^{-1}$ in 1992 to 150 kcal $cap^{-1}$ $day^{-1}$ in 2001 (FAO 2002a). Under nourishment is limited to 5% of the population, equal to 3 million people. Consumption levels are presently increasing again, but it will take several decades before the high consumption patterns of the communistic period are reached.
- The population in the Ukraine is expected to decrease during the coming decades as has been the case since the early 90's. The population is expected to decrease from 50 million to 32 million in 2050 (medium population scenario). The decreasing population and the recent decrease in food consumption and slow projected increase in food consumption limits the total increase in food demand and thus limits the future demand for agricultural land.
- The combination of fertile chemozems soils (black soils) and a temperate continental climate in the Ukraine make this country one of the most (potential) productive regions for grain farming in the world. Presently only a very limited part of this potential of the Ukraine as a grain producer is presently used. The FAO reports that typical average yields achieved by the collective and state-owned farms during the 1980's, were 3 ton per hectare for winter wheat and 25 to 30 ton per hectare for sugar beet. These yields have declined to as low as 2 ton per hectare for cereals and 10 ton for sugar beet. Experience has shown that cereal yields, even on large collective farms, can reach 7 to 8 ton per hectare and can be maintained at that level without any apparent negative effects on the environment. Sugar beet yields can reach 60 ton per hectare with relatively simple technologies (Dixon *et al.* 2001).

The recent decrease in consumption, production and yields indicate that the Ukraine is presently producing much less than it is capable of. If the agricultural sector in the Ukraine manages to increase the productivity per hectare and the future increase in consumption is limited as projected, than the agricultural land use may decrease and land may be made available for bioenergy production. The potential for bioenergy is analysed below.

**Land resources**

The Ukraine covers 58 million hectares land. This 58 Mha can be subdivided into land various land use categories as shown in figure13.

*Figure 13.* Land use pattern in the Ukraine in 1995 (left) and land suitability profile of land area not under forest cover in 1995 (right). VS = very suitable, S = suitable, MS = marginally suitable, mS = moderately suitable and NS = not suitable. Sources: (FAO 2000b, 2002a).




In total some 70% of the total land area in the Ukraine is used as agricultural land (arable land, permanent crops or permanent pasture). The right part of figure 13 shows the suitability for crop production of areas not under forest cover to indicate the agro-economic suitability. The areas not under forest cover are allocated to agriculture and/or are occupied by build-up land and other land. In total, 73% of the land area of the Ukraine is very suitable, suitable or moderately suitable for crop production. Of this 78%, 93% is presently not under forest cover thus in potential available for agriculture (excluding land use for other purposes). This 93% equals 43 million hectares and is slightly larger than the 41.6 million hectares agricultural land presently in use.

**Efficiency of production**

Substantial gains in the efficiency of production can be reached in the Ukraine, dependant on the level of inputs and if agriculture in the Ukraine is concentrated on the most suitable areas. Table 12 shows the potential to increases crop yields and efficiency of the animal production system compared to 1998. Scenarios which lead to food shortages or decreases in yields are excluded.

*Table 12a.* Potential to increase crop yields in the Ukraine based on various levels of technology (1998 yield level = 1). Based on the food demand in 2010 and a high feed conversion efficiency and a mixed production system.

| (1998=1) Crop<br>Level of technology | all crops | cereals | roots and tubers | sugar crops | pulses | oilcrops |
|---|---|---|---|---|---|---|
| intermediate, rain-fed | 2.2 | 2.6 | 1.5 | 2.3 | 3.5 | 1.2 |
| high, rain-fed | 2.8 | 3.8 | 3.3 | 1.2 | 2.9 | 2.9 |
| mixed, rain-fed | 3.0 | 3.5 | 1.3 | 2.9 | 5.3 | 1.8 |
| mixed, rain-fed/irrigated | 3.5 | 3.6 | 2.9 | 3.2 | 5.7 | 1.9 |

*Table 12b.* Potential to increase the feed conversion efficiency in the Ukraine based on a high feed conversion efficiency (1995 feed conversion efficiency = 1).

| (1998=1) Product<br>Level of technology | bovine meat | pig meat | poultry meat | milk, ex. butter |
|---|---|---|---|---|
| high feed conversion efficiency | 1.4 | 1.2 | 1.3 | 1.4 |

The potential to increase crop yields is on average considerable, between a factor 2.2 and 3.5. The crops with the highest potential yield increases are cereals and pulses. These data are in line with data from the FAO, that reports a potential increase of wheat yields of 2.5, from 2.5 ton per ha to 6.2 ton per hectare, with a variation of 3.6 on the most suitable soils to 1.8 on moderately suitable areas (FAO 2002b). The potential to increase the productivity of the animal production sector is less dramatic, but still between 20% to 40%, dependant on the type of animal. The reason for this limited increase is that production systems in the Soviet period have been fairly efficient with high feed conversion efficiencies and because present production is based on an intensive, mixed production system.

**Potential for bioenergy production**

Modelling results show that the Ukraine is capable of freeing several million hectares land for bioenergy production, without endangering the food demand in 2010. In a mixed rain-fed/irrigated production system some 25 million hectares can be made available (surplus) for bioenergy production, while in a rain-fed intermediate input system 'only' some 20 Mha can be made available. Based on a high level of technology for bioenergy crop production and the suitability of the surplus land areas for bioenergy production, average yields for woody bioenergy on the surplus areas range between 17-21 ton dry weight per hectare. The total bioenergy production potential in the Ukraine ranges between 6 $EJy^{-1}$ and 10 $EJy^{-1}$ (based on a HHV of 19 GJ per ton dry weight biomass).

Due to the many uncertainties related to various parameters in this study, further research is required to allow assessments of the (regional) implementation potential and to make more accurate bioenergy potential assessments. Key-priorities for future research are:

- Data reliability and availability. There is a particular lack of data on the following issues:
  - use and sources of fuelwood,
  - feed composition and feed conversion efficiencies,
  - production capacities of natural pastures and the impact of various management systems,
  - the implications of sustainable forest management on yields levels.
- The dynamics on the socio-economic system that determines land use patterns and yields. To what extend the technological potential calculated in this study can be realised realistically, remains to be seen. In reality, yields are the result of many complex iterative interactions between included in the entire socio-economic system (e.g. prices of land and labour, available infrastructure, trade negotiations, interest rates, education level of agricultural workforce). These complex interactions are poorly understood and are very difficult the quantify (IFPRI 2001b) (Döös and Shaw 1999).
- The extend and severity of environmental degradation and the impact of various management systems. The are considerable uncertainties related to the many biological and physiological processes that determine the earth' carrying and regeneration capacity. These uncertainties could be included in the first issue on data reliability and availability, but due to its potential impact on agriculture and it's importance in discussions on agriculture and bioenergy production, we decided to mention it specifically. Studies on these issues are notoriously uncertain and dependant on expert knowledge (Döös and Shaw 1999; IFPRI 2001b). As a result, the impact on agriculture of various forms of environmental degradation (vice versa) such as fresh water depletion, soil degradation (salinisation, soil depletion, desertification, loss of topsoil) and loss of biodiversity is difficult to estimate. Due to the many uncertainties, estimates or the perception of the seriousness of these issues and the consequences for agriculture (and vice versa) vary widely. E.g. a review of publications of the earth carrying capacity shows that estimates range from 1 billion to 157 billion (Cohen 1995). Despite these uncertainties however, there is a general agreement that *'most forms of environmental degradation and overuse are caused by an improper use of resources or can be reduced or prevented by an appropriate mix of policies and technological changes'* (e.g. (UN 1993; Alexandratos 1994). In many developing regions, environmental degradation, health and poverty are closely related. Additional income in these regions from bioenergy production and trade may provide the necessary incentives and funds to increase productivity, reduce

poverty and reduce environmental degradation. At this moment, bioenergy production certification schemes are under development to ensure environmentally and socially sound production systems.

Considering the large uncertainties described, as a follow-up of this study a regional analysis of the bioenergy production potentials in Brazil and the Ukraine is carried out. The methodology to estimate bioenergy potentials and analyse land use patterns is used as a basis for these case studies. In addition, the more regional analysis makes a more detailed analysis possible of land use patterns and particularly the impact on the functioning of the socio-economic system and the various forms of environmental degradation. Specific attention is paid in this project to the impact that various criteria may have on the potential for bioenergy.

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## APPENDIXES

## APPENDIX A

## REGIONAL CLASSIFICATION

Table 1 and figure 1 show the regional breakdown used in this study. In total the world is divided into 19 regions.

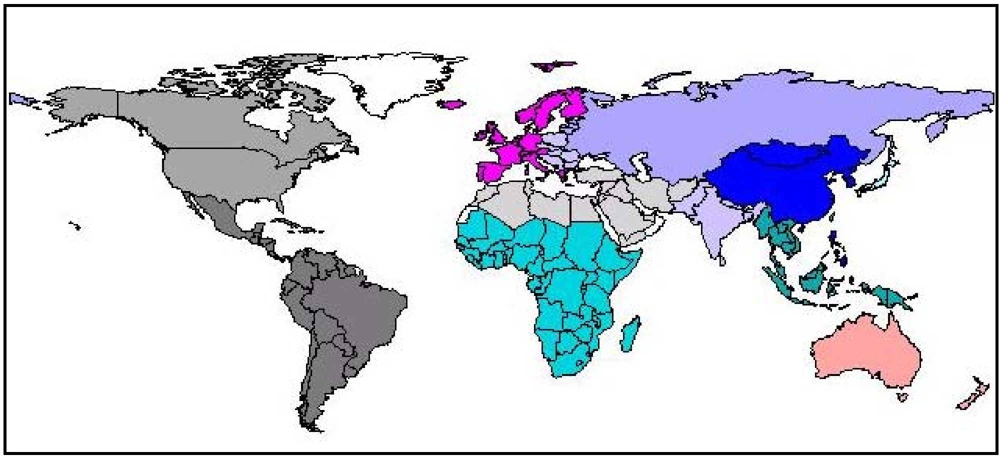

*Figure 1.* Regions used in this study (white areas are excluded).

*Table 1.* Regional aggregation used in this report.

| Region | Aggregated region |
|---|---|
| West Africa | |
| Central-Africa | 1. Sub-Saharan Africa |
| East-Africa | |
| Southern-Africa | |
| Caribbean | |
| Central America | 2. Caribbean & Latin America |
| South-America | |
| North Africa | 3. Near East & North Africa |
| Near East | |
| East Asia | 4. East Asia |
| South-East Asia | |
| Northern South Asia | 5. South Asia |
| Southern South Asia | |
| 6. North America | |
| 7. Oceania | Industrialised countries |
| 8. Western Europe | |
| 9. Japan | |
| 10. East Europe | Transition economies |
| 11. C.I.S. and Baltic States | |
| | World |

The selection of regions is based on continental boundaries (Oceania, North America), climate zones (sub Saharan Africa), regions with comparable production systems, economic structure, level of development, political system and/or data availability (Western Europe, former Eastern

Europe) or geographic regions (sub-Saharan Africa, South East Asia). Data for the developing countries are considered less reliable than for other regions. Therefore, the results in this study are aggregated into 5 developing regions, 4 industrialised regions and 2 transition economies-regions, indicated by number 1 to 11 in table 1.

This level of aggregation may be considered as a common level of detail used in studies on global food demand and supply and is comparable with that used in e.g. the FAO report Agriculture Towards 2015/2030. Many other studies, notably studies on (fuel)wood consumption, are based on less detailed regional breakdown. Overlap in regions used in different reports occurs frequently and is a handicap when comparing and combining results and data. For practical reasons and to flatten out errors, data are only shown for North America, Oceania, Japan, Western Europe, East Europe, C.I.S. and Baltic States, sub-Saharan Africa, Caribbean & Latin America, Near East & North Africa, East Asia, South Asia and the World.

## APPENDIX B

### HISTORIC CONSUMPTION PATTERNS

During the last decades average food (energy) intake per capita has steadily increased in most regions in the world, on average from ca. 2360 mid 60's to 2800 kcal $capita^{-1}$ $day^{-1}$ at this moment (FAO 2003b). This progress reflects mainly the increase in consumption in the developing countries, because average consumption levels in the industrialised and transition economies were already fairly high in the mid 60's (FAO 2003b). This has been achieved despite increases in population in especially the developing countries. The result is that the share of undernourished people has decreased significantly, but it is unlikely that the absolute number of undernourished people declined much (FAO 2003b)[27]. Figure 2 shows the daily calorie intake per capita in different regions. Data are based on country specific numbers derived from the FAOSTAT database (FAO 2002a).

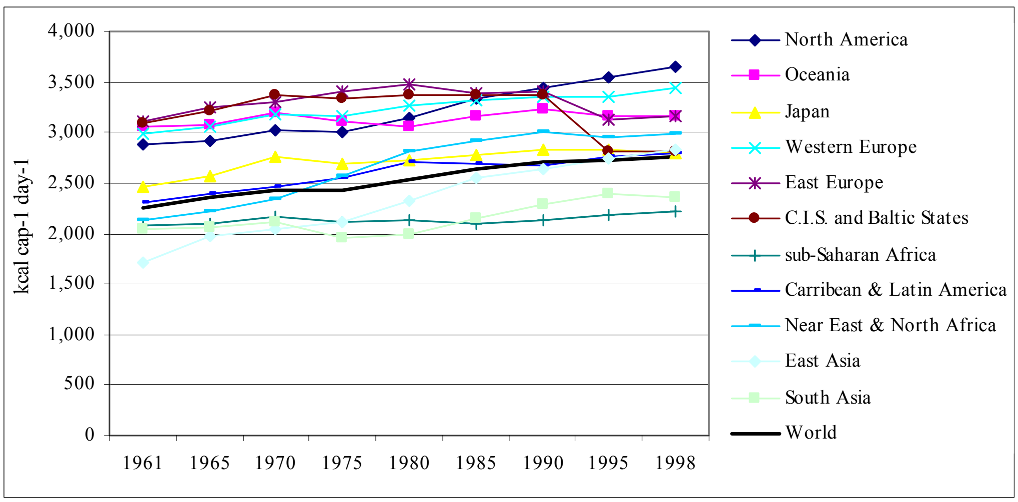


*Figure 2.* Daily food intake in kcal per capita. Source: (FAO 2002a).

There are large regional differences in total food intake and increase over the last decades.

The lowest progress was made in sub-Saharan Africa with an average increase from ca. 2000 kcal $capita^{-1}$ $day^{-1}$ in 1960 to 2250 kcal $capita^{-1}$ $day^{-1}$ in 2000. South Asia has only since the late 80's made some progress in achieving a middle level of food intake of ca. 2400 kcal $capita^{-1}$ $day^{-1}$. Main reasons for the developments in Sub-Saharan Africa and South Asia are the rapid population growth and general poor economic performance.

East Asia (including the populous China) made much progress and has now a medium to high consumption level (2783 kcal $capita^{-1}$ $day^{-1}$; 2700 kcal $capita^{-1}$ $day^{-1}$) (FAO 2000a). Consumption levels in Latin America increased steadily between 1960 and 2000, from ca. 2350 to 2840 kcal $capita^{-1}$ $day^{-1}$. In the North Africa and the Middle East regions consumption has increased significantly from ca. 2120 to 2950 kcal $capita^{-1}$ $day^{-1}$, the highest consumption level of the developing regions.

[27] In FAO (2000) undernourishment is defined as a daily intake of less than 2000 to 2310 kcal (based on moderate activity level and the current demographic composition of the developing countries).

The industrialized countries and transition economies had already fairly high levels of consumption since the mid-60's of more than 3100 kcal per capita per day (FAO 2000a). In East Europe and the former USSR however, food intake has dropped since the fall of communism in 1992. Economic restructuring caused a decrease in GDP, abandonment of subsidies and an increase in food prices resulting in decreasing food consumption (mainly due to decreased intake of animal products). Average calorie intake increased again in 2000 according to FAO statistics (Liefert and Swinnen 2002). The consumption in the industrialized countries is presently the highest with an average of ca. 3425 kcal capita$^{-1}$ day$^{-1}$. Detailed analysis of consumption patterns showed that consumption levels in the industrialized countries are levelling off, mainly due to stagnating intake of animal products.

## INTAKE OF ANIMAL PRODUCTS

In this study specific attention is given to changes in the consumption of animal and vegetal products, because in the last decades the increased production of animal products has a major impact on the agricultural sector and its land use patterns, because the production of animal products is more land intensive than the production of crops (Luyten 1995).

Globally, the intake of food from crops increased from 1917 to 2346 kcal capita$^{-1}$ day$^{-1}$ (+22%); the daily intake from animal products increased from 338 to 459 kcal capita$^{-1}$ day$^{-1}$ (+35%) (FAO 2000a, 2002a). Thus, consumption of animal products has thus increased both in terms of daily kcal intake and in share of animal production in the total intake. Regional averages in daily intake in kcal are shown in figure 3.

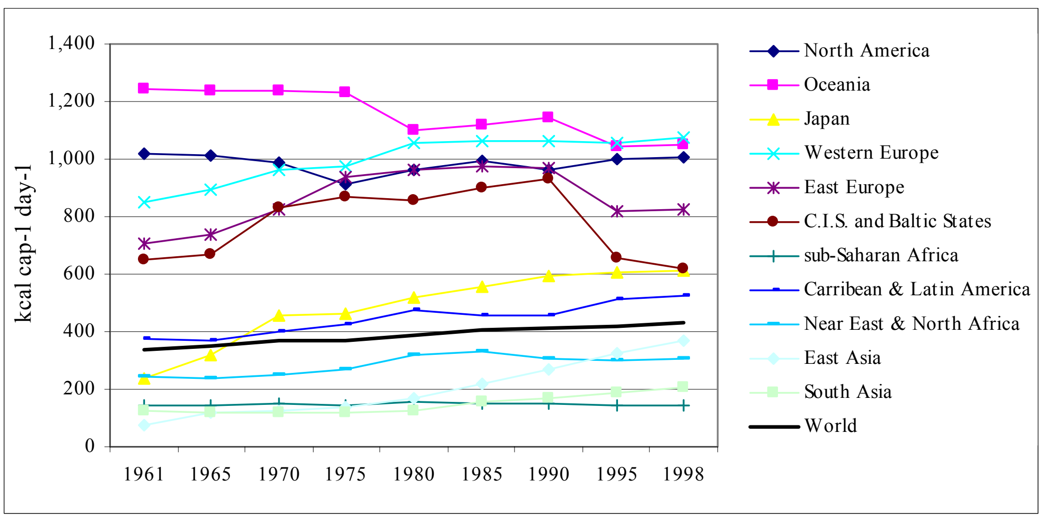


*Figure 3.* Daily intake of animal products in kcal capita$^{-1}$ day$^{-1}$. Source: (FAO 2002a).

Figure 3 shows that in Eastern Europe and the countries of the former USSR consumption have decreased since the fall of communism in 1992. Before the fall of communism, these countries were producing and consuming livestock products at a much higher volume than one would expect based on the countries' real income (Liefert and Swinnen 2002). The GDP per capita was about half of that in the Europe and North America, but levels of consumption of most foodstuffs which were slightly less than most of the Western countries. This 'miracle' could only exist due to large state subsidies, to both producers and consumers, were necessary to maintain the high levels of production and consumption. The bulk of the subsidies went to the livestock sector. Since the economic reforms GDP and consumption have fallen considerably. This goes especially for meat and dairy products. The freeing of prices has caused an economy wide inflation, thus decreasing real GDP per capita and increasing consumer and producer prices.

Data for the '90's for China given by the FAO are estimates based on national data and estimates of production and net trade (Delagdo 1999). The International Food Policy Research Institute reports that the that consumption levels are overestimated by 26% (Delagdo 1999). For practical reasons and because we considered it impossible to judge whether the IPFRI data are more accurate than the FAO data, the FAO data were not changed. Note that even without this overestimation, the increase in consumption of animal products remains spectacular.

Sub-Saharan Africa has the lowest intake of animal products, resulting from poor economic performance. Consumption in South Asia has remained low, partially as a consequence of religious considerations against the consumption of animal products, which also has its impact on overall consumption.

As shown in figure 3, the consumption of animal products has grown considerably in Japan, but remains low compared to other industrialized countries. In Japan exceptionally much seafood is consumed. Growth in Western Europe and Oceania has been little and has decreased in North America during the past twenty-five years. Consumption seems to be levelling off in these regions (Delagdo 1999).

## APPENDIX C

## METHODOLOGY OF COMPOSING THE CONSUMPTION SCENARIOS

Historic time series (1961-1998) of the total consumption in kcal capita$^{-1}$ day$^{-1}$ for vegetal products, animal products and fish and seafood were taken from the Supply Sheets from the FAO database (FAO 2002a). Data are given per country and regionally aggregated. The calculated consumption was allocated to different consumption categories based on foodstuff specific daily kcal intake per capita given in the Food Balance Sheets (FBS) derived from the FAO database (FAO 2002a). The data are the average for the years 1997, 1998 and 1999. The data include the total supply: production, losses, import and export and the use for food, feed use, seed and processing. Figure 4 gives an overview of the data and steps of the composing of the consumption scenarios.

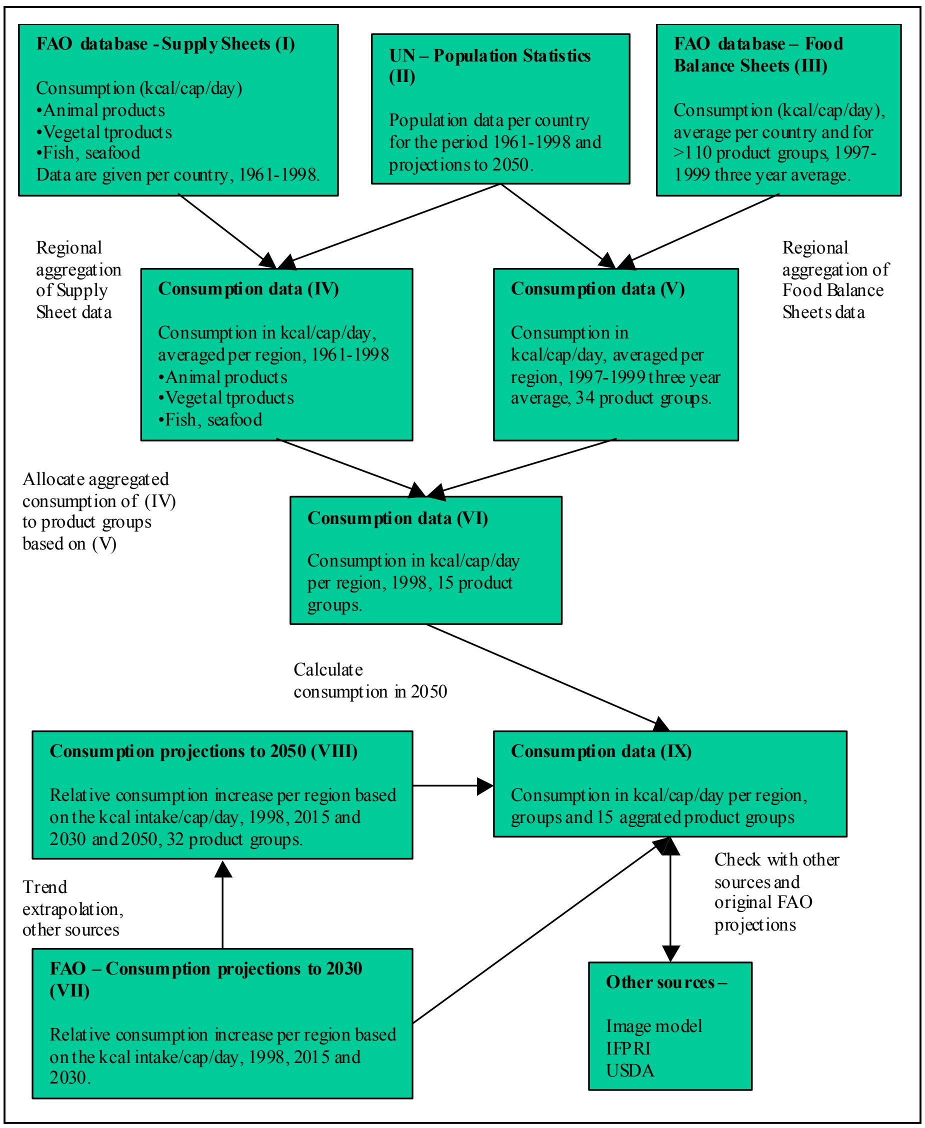


*Figure 4.* Overview of the composing of the consumption scenarios.

The future demand for crops is based on the *relative* increase in kcal projected by the FAO to 2015 and 2030 (FAO 2003b), that may be considered as one the most authorative and important study on the long-term future of the agricultural sector available at this moment. Detailed datasets per region were obtained via the FAO. Regions included were West Africa, Central-Africa, East-Africa, Southern-Africa, Caribbean, Central America, South-America, North Africa, Near East, East Asia, South-East Asia, Northern South Asia, Southern South Asia, transition economies and industrialised countries and data were available for 1998, 2015 and 2030. Data for consumption of fish were derived from the main report (FAO 2003b), although the data are less detailed than for other consumption categories. The projections received from the FAO were aggregated per product category because of differences in classification, regional aggregation and differences unaccounted for. Trend extrapolation was used to extrapolate data to 2050. The FAO projections were supplemented by data from other sources and own guestimates when:

- the definition of regions used in the FAO projections did not match with the regional breakdown used in this study,
- the extrapolated consumption increases seam unrealistically high or low compared to other regions and data from other sources because of:
    - differences in base year data between the FAO projections and
    - differences between the calculated base year data used in this study and the Feed Balance Sheets data compared to the FAO projections and/or similarly when the extrapolation of GDP growth figures yield unlikely high or continued low estimates
    - the calculated total relative increase is too low or high because of low total consumption and the impact of rounding. This in combination with small differences in base year data means that overall consumption increases are blow out of proportion our too low.

Base year data on consumption from the FBS are adjusted to match the historic trend in daily per capita kcal intake from the Supply Sheets. Growth percentages for crops are aggregated into 6 commodity groups (cereals, pulses, sugar crops, oil crops, roots & tubers, vegetables & fruit, spices, stimulants, alcoholic beverages). The categories animal products (6) were not aggregated: bovine meat, pig meat, poultry, mutton meat, eggs and milk because the consumption of animal products requires a higher level of detail because of the relative land intensive animal production system and large differences in land use between different animal products.

The final consumption increases match the FAO projections (except in the case of differences in definitions of regions), although due to the combination of different datasets and projections, minor differences are present. To reflect the uncertainty related to projections of food consumption, a high and low scenario are calculated. The high scenario is based on an additional increase in consumption of 50% compared to the baseline increase between 2030 and 2050 (=100%). The low scenario is based on 50% of the growth between 2030 and 2050. We hope that the inclusion of high and low projection to 2050 reflects at least some of this uncertainty, although it can not be excluded that future developments fall without the projected range.

## REGIONAL ADJUSTMENTS

Several adjustments were made to the original consumption scenarios based on projections from the IMAGE model (IMAGE-team 2001) and the International Food Policy Research Institute (IFPRI 2001a). The IFPRI projections are results from their Integrated Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT). This model includes full supply and demand matching using elasticities and is aimed at calculating a baseline scenario for 2020 as well as exploring the effects of alternative scenarios. Because of the limited regional breakdown, time horizon (2020) and the general scientifically accepted mode, the projections from the FAO were used, although the results in this study are compared to those of the IFPRI. The IMAGE model is an integrated assessment model that explores the effects of four different storylines[28]. These storylines show clearly the effects of different developments and policy options. The storylines vary on issues such as the development of income (e.g. the A1 scenario projects there is a rapid closing of the income gap between the developed and developing countries), the development of technology (e.g. the development in yields) and the level to which policies are implemented to prevent environmental degradation (e.g. limit the use of fertilizers and pesticides). Thus, no 'most likely scenario' is calculated. All four scenarios are all considered plausible. Because the four consumption scenarios are the result of supply and demand matching including different assumptions the consumption scenarios may not be used separate from these assumption or in combination with separate supply scenarios as used in this study. However, the IMAGE consumption scenarios span a wide range of consumption scenarios, which are all considered somewhat plausible and are thus useful compare with the range of consumption scenarios used in this study as described below.

For the C.I.S. & the Baltic States and Eastern Europe the FAO projections give one aggregated consumption scenario for transition economies. The same goes for the industrialised regions (Western Europe, North America, Japan and Oceania).

For Eastern Europe projections from the International Food Policy Research Institute (IFPRI) were used to project the consumption of animal products (excluding fish and seafood). The baseline scenario indicates that the consumption of meat in East Europe is expected to increase by ca. 21%, eggs by 2% and milk by 25% to 2020. The projected relative increase of different animal products (e.g. a relative large increase of land extensive poultry meat vs. slowly increasing consumption of land intensive bovine meat) is taken from the FAO consumption scenario. Extrapolation to 2050 shows that consumption levels in Eastern Europe will have reached saturation level for animal products used in this study by 2050 (+30% above the 1998 level). A similar development is projected by the IMAGE model, which projects a consumption of more than 1050 kcal capita$^{-1}$ day$^{-1}$. Note that the total kcal intake per capita in 2050 is projected to lies above Western European levels, as is also projected by the IMAGE model.

For the C.I.S. & the Baltic States area, no region specific projections were available so the FAO projections for transition countries was used. This could lead to an overestimation, because Eastern Europe is doing quite well in achieving higher consumption levels, but at least it does not lead to an underestimation of the land required for consumption. This overestimation is likely to be limited, because the CIS/Baltic states area has a larger population than Eastern Europe and thus the overall projections reflect more the change in consumption in C.I.S. & the Baltic States

[28] The four IPCC SRES scenarios are: A1: future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology. Major underlying themes are economic and cultural convergence and capacity building, with a substantial reduction in regional differences in per capita income. In this world, people pursue personal wealth rather than environmental quality. A2: a very heterogeneous world. The underlying theme is that of strengthening regional cultural identities, with an emphasis on family values and local traditions, high population growth, and less concern for rapid economic development. B1: a convergent world with rapid change in economic structures, "dematerialization" and introduction of clean technologies. The emphasis is on global solutions to environmental and social sustainability, including concerted efforts for rapid technology development, dematerialization of the economy, and improving equity. B2: world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is again a heterogeneous world with less rapid, and more diverse technological change but a strong emphasis on community initiative and social innovation to find local, rather than global solutions.

than in Eastern Europe. For the consumption of vegetal products no regional data were available, so the FAO scenario for transition economies is used for both Eastern Europe and the C.I.S. & Baltic States area. The overall calculated increase in consumption in the transition countries is from 2913 kcal capita$^{-1}$ day$^{-1}$ to 3243 kcal capita$^{-1}$ day$^{-1}$, slightly more than the 3180 kcal capita$^{-1}$ day$^{-1}$ projected by the FAO (FAO 2003b), but within an acceptable range.

For Japan no country specific data were available, except for the consumption of which is estimated by the IFPRI at 52 kg per capita in 2020 (IFPRI 2001a), an increase of 27% compared to 1998. This growth percentage is also used for milk and eggs. To 2015 this annual growth percentage was used. The extrapolated projection to 2030 is based on half this growth ratio resulting in a 743 kcal capita$^{-1}$ day$^{-1}$ intake, similar to the range of 722-771 kcal capita$^{-1}$ day$^{-1}$ projected by the IMAGE model (IMAGE-team 2001). For 2050 the IMAGE value of 795 kcal capita$^{-1}$ day$^{-1}$ (A1 scenario) was used as medium level not to underestimate the demand for animal products. The consumption of vegetal products is assumed constant (the increase is less than 1% as projected by the IMAGE model; even to 2100 the increase in consumption of vegetal products remains relatively stable +4%).

For all industrialised regions the overall trend projected for the industrialised regions was used. Using this overall trend the calculations shows a slow increase for Western Europe and North America, where consumption quickly reaches saturation. This overall trend is most likely an underestimation of the growth in consumption in Oceania where consumption levels are significantly lower (2103 kcal capita$^{-1}$ day$^{-1}$ in 1998 vs. 2636 and 2363 kcal in North America and Western Europe), mainly the result of lower consumption of vegetal products. Therefore the scenario for the consumption of vegetal products was upscaled +2% for both 1998-2030 and 2030-2050.

For two regions the trend extrapolated consumption levels were downscaled. These were South Asia and East Asia to correct for illogical trend extrapolations. Both regions are projected to have significant economic growth, but it is unlikely that the projection per capita growth rates of 4,1 and 5,5% for South Asia and East Asia to 2030 will continue an additional 20 years. Growth of consumption for the period 2030-2050 is projected at half the growth rate of 2015-2030, both for vegetal products and animal products.

For sub-Saharan Africa the trend has been upscaled. In 2030 a still relatively and sometimes dangerously low level of consumption is projected for this region of 2576 kcal capita$^{-1}$ day$^{-1}$ in 2030; well below all other regions. This leaves ample room for increasing consumption before saturation levels are reached. Trend extrapolation could thus underestimate consumption in 2050 assuming the possibility of faster economic progress then projected to 2030. Main problem is the low economic growth of 2.0% increase in per capita GDP per year (1998-2030), the lowest of all regions, compared to 2,6% global average and 4,0% of the developing countries. A rapid consumption increase of especially animal products can be expected when per capita income increases. Assuming the possibility of higher GDP growth after 2030, consumption scenarios for the consumption of animal products are upscaled by 50% above the growth rate of 2015-2030. The consumption scenario for vegetal products is not changed, because the strong pressure to increase consumption levels translates in already high increase of vegetal products; it's especially the intake of animal products that makes the difference.

According to the IFPRI, the consumption of animal products in China may be overestimated by 21% in the FAO statistics (Delagdo 1999). This issue is not taken into account in this study.

## APPENDIX D

## THE CORRELATION BETWEEN INCOME AND FOOD CONSUMPTION

The most import driver for consumption is income (Sanderson 1988; FAO 2000a). The income elasticity is especially strong with the consumption of animal products (*income elastic*) (FAO 2000a; Liefert and Swinnen 2002). The correlation between GDP ppp (power purchase parity) and meat and dairy consumption is shown in figure 5.

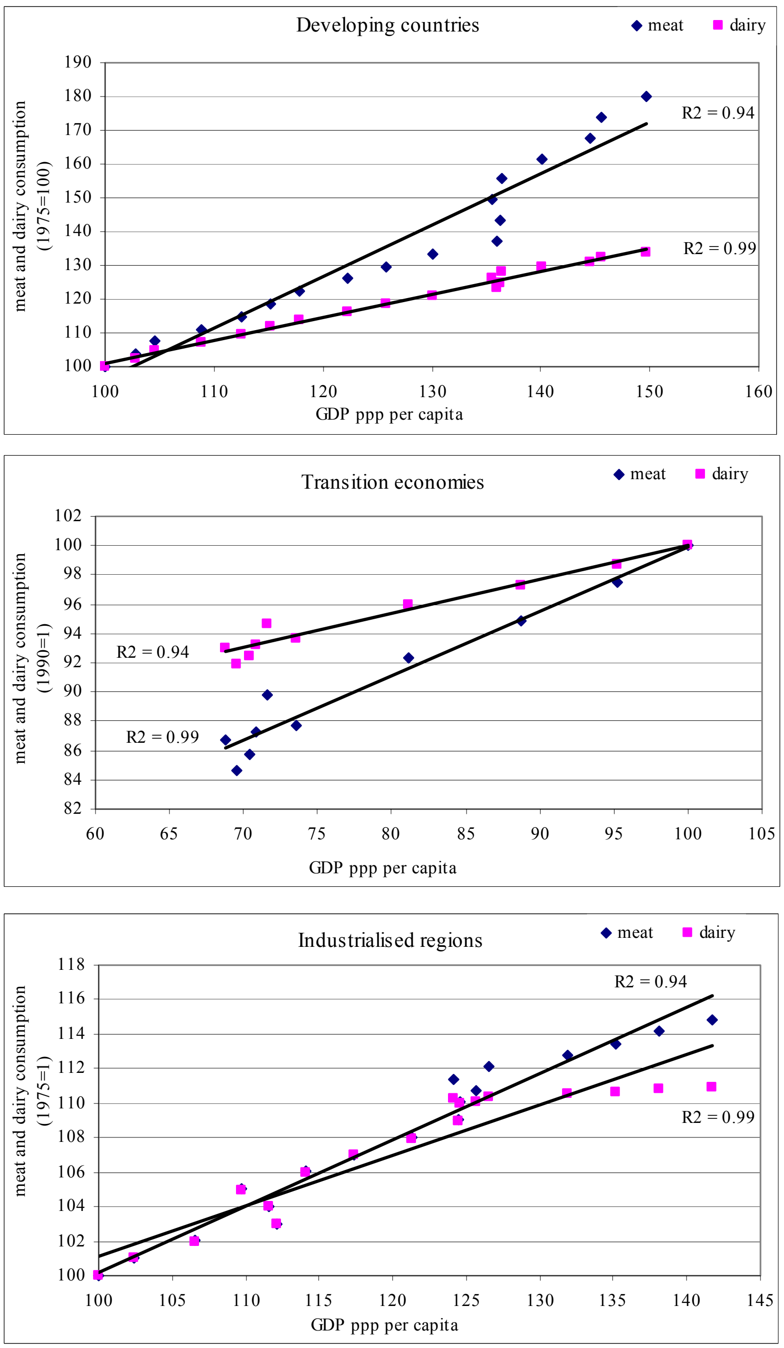


*Figure 5.* Correlation between GDP ppp and the consumption of animal products. Source: (FAO 2000a; UNEP 2002a).

Table 2 shows the calculated income elasticities (data for transition economies are not calculated because the correlation is blurred with the effect on prices of subsidies and economic reforms). As can be expected, the demand elasticity is the largest in the regions with the lowest consumption of animal products and the lowest GDP.

*Table 2.* Demand elasticities of animal products (based on an assumed linear correlation; consumption and GDP ppp data from 1975 to 1992). Sources: (FAO 2000a; UNEP 2002a).

| | Developing countries | Industrialized countries |
|---|---|---|
| Meat | 0.94 | 0.38 |
| Milk | 0.68 | 0.29 |

It can be seen that consumption patterns in the developing countries are much more sensitive to changes in GDP than in the industrialized world, which partially have reached saturation levels. 1% increase in income results in an increase of 0.94 % in meat and 0.68% in milk consumption in the developing countries; figures for the industrial countries are 0.38 and 0.29% respectively. Other studies indicate a similar difference in response to income growth based (Schroeder 1995), but a stronger correlation in general.

Based on the observations above, it can be fairly stated that there is a strong drive to increase the consumption of animal products. However, the use of the calculated correlation coefficients for projecting consumption is very problematic for several reasons as described in the following section.

## METHODOLOGICAL PROBLEMS MODELLING DEMAND AND SUPPLY USING ELASTICITIES

The elasticities, calculated as described in the previous section, clearly indicate the strong correlation between income and consumption but are of little use for projecting future consumption levels. The combination of the calculated regionally aggregated elasticities with less geographically aggregated or country specific data leads to unrealistically high or low consumption levels. This problem can be overcome, by calculating elasticities based on country specific GDP ppp and consumption data of animal products. This however, shows trends blurred in the aggregated regions such as large regional, year-to-year differences resulting from e.g. cultural differences in consumption patterns, regional price differences, natural circumstances as droughts or floods or shifts in agricultural policy, trade liberalisation etc. (data not shown). Specific examples are: consumption levels in China are rather high compared to the GDP, reflecting the importance of pork in Chinese diets, while in Muslim countries pork is excluded from the diet. In India consumption levels are very low because of religious arguments against the consumption of meat (Delagdo 1999); due to lactose intolerance in mainly East Asia milk consumption is limited and meat consumption in Japan is not so much limited by GDP, but by import restrictions (IFPRI 2001a). In the developed world the attention for health caused a shift in the consumption composition from red meat to lean meat such as poultry meat.

Consequently, region specific elasticities may be considered as unrealistically high or low. When developing the IMAGE model, analyses of elasticities calculated this way for 13 regions showed that ca. 40% of the calculated elasticities had to be adjusted (Alcamo *et al.* 1994).

Further, real changes in consumption are much more complex than can be calculated accurately using a simple model based on the correlation between GDP and consumption only. For one thing, the data in figure 5 are based on historic developments in GDP and consumption between 1975 and 1992. Thus, they do not include price changes. In reality, food prices decreased steadily in the last decades (IFPRI 2001a; FAO 2003b). The calculated coefficients from figure 5 thus overestimate this correlation. This problem could be overcome by 1.) calculating elasticities based on consumption and GDP ppp data for *one year* across different regions instead of time series for one region. The more regions included, the less impact distorting factors (e.g. cultural consumption patterns, trade barriers) have on the correlation GDP – consumption, but the less region specific the data become. 2.) supply and demand modelling, although such an exercise is very complex because it requires data on production costs, GDP, prices and elasticities thereby aggravating the problem rather than solving it.

An additional problem is that income elasticities tend to vary considerably over time with changing consumption (income) (Delagdo 1999; Rosegrand 2001) as can also be seen in the difference in elasticities between developing and industrialized countries showed in figure 5. Further, in general GDP data expressed in power purchase parity (ppp) are used. Ppp means that the GDP data is corrected for price differences between countries and regions and reflect (more than GDP data based on exchange rates only) the actual purchasing power. The GDP ppp data are based on a fixed basket of goods, exchange rates and local prices. A valid question is to what extend GDP ppp data represent actual purchase power for foodstuff. Prices for agricultural crops have steadily decreased in the last decades, world market prices for wheat, maize and rice are the lowest they have been in the last century (adjusted for inflation) (Pinstrup-Andersen 1999). This decrease in food prices directly benefits the poor who spend a large part of their income on purchasing food. A GDP ppp based on foodstuff basket may have changed (most likely decreased) than a GDP ppp based on an average basket. The use of Big Mac index (GDP expressed in ppp specific for foodstuff, in this case the Big Mac hamburger would be more appropriate. Secondly, increasing domestic prices (inflation) is reflected in a lower exchange rate to other currencies, but exchange rates can also vary due to other reasons.

Three examples clearly illustrate the complexity of food consumption patterns.

- There is general consensus that under nourishment is not just a problem of GDP (poverty). In many developing regions poor government, war and corruption significantly add to the problem. Therefore, it is difficult to project future consumption patterns for regions with low food intake based on quantitative correlation of historic trends.
- In 1993 and 1995 there has been a global decrease in cereal consumption and production due to bad harvests in different parts of the world, changes in policy and various other reasons. Stock levels were very low and prices high. It was feared at that time that these were the first signs that the world was running out of resources for food production and yield ceiling were reached, resulting in a number of scientific papers. However, fuelled by the high food prices in that period, global food production systems responded quickly. In 1997 and 1998 production was an all time record with historic low prices.
- Urbanization is identified as strong driver for increasing meat consumption (Delagdo 1999). Consumers in urban areas typically prefer a more meat intensive consumption pattern, although the effect could be overlapping with increasing GDP in developing countries. Due to a lack of quantitative data on the correlation between urbanization and consumption and overlap between this effect and the correlation between GDP and consumption (per capita GDP is generally higher in urban areas).

Consequently, a considerable amount of expert judgement is required to make projections of future consumption patterns, although not so much for the short term, but mainly for the long-term such as to 2050. The International Food Policy Research Institute (IFPRI) uses a system of supply and demand elasticities, incorporated into a set of linear and non-linear equations (IFPRI

2001c), but the origin of the given values for the elasticities are not further discussed. The influential FAO report ‘World Agriculture: Towards 2015-2030’ is mainly based on expert judgement and is also frequently used in this study (FAO 2003b). Conclusions on the overall reliability of these and other projections are shown in Appendix O and P.

## APPENDIX E

## POPULATION GROWTH

Population projections are published by a limited number of organisations. The most important is the United Nations Populations division (UNPD), which publishes regularly updated and revised population data for six long-term scenarios. Two other institutions which also publish population projections are the International Institute of Applied Systems Analysis (IIASA) (Lutz 1996) in Austria and the United States Census Bureau (USCB 2002). In this study the population projections of the United Nations Population Division are used (UNPD 2002) because:

- the UNPD has become the main authority in this field and are the most frequently used and cited and scientifically accepted source (as e.g. in the FAO outlook study on global trends in agriculture 'Agriculture Towards 2015/2030' of which data are used in this project (FAO 2000a),
- they are regularly updated and thus based on the latest insights (the IIASA projections are published in 1996),
- they include different scenarios and indicate the range within the population is most likely to lie within.

There is general agreement among demographers that population projections - if properly done - *are* 'fairly accurate for some 5 to 10 years' (Heilig 1996). This because the number of children is dependent on the number of young adults in a population and this number is known from existing population data. Theoretically it is possible that there will instantly and significantly change from the previous generation, but this is very unlikely (Fisher 1997) to happen. This effect is called the population momentum and is reflected in the fact that the different projections differ increasingly more with increasing time horizon. Unexpected events such as global economic crisis, world war III, outbreaks of lethal diseases etc. are not (never) included in the projections.

Long-term population projections however have proven to be quite uncertain, e.g. in the early 60's most projections for the developed countries where much too high. With the experience of a "baby boom" no one had expected the massive drop in fertility during the early 1970s and the continuation of below-replacement fertility in the 1980s, and 1990s (Heilig 1996). Therefore, population projections tend to change significantly over time. An evaluation of past population projections from the UNPD revealed that Global aggregated projections had an projection error between +0.5 and +7% (IFPRI 2001b):

- as the time frame lengthened, -4.8% for the 5 year projections, to +17% for 30 year projections.
- as projection were disaggregated. Regional forecasts from 1957 made for 2000 show errors that differ between –35.4/+30.8%
- for the developing countries compared to industrialised countries.

To reflect the uncertainty related to (population) projections, the UNPD publishes six different scenarios that vary on the rate of mortality and fertility and the level of migration. These are the three components of the model used to calculate the future size of population. The medium scenario is the most likely scenario. The high and low scenario vary on the level of fertility (but not on mortality or migration) and it is 'very unlikely' that population growth will fall without the projected range. In the high/low scenario the fertility rate is set at 0.5 child above/below the medium fertility rate (UNPD 2003). here seems to be no clear scientific basis on which this figure is based and no probability is given for this assumption. Note that the uncertainty related to population projection increase in the last years, since the population projection published in the last decade have been frequently downscaled by more than 10%.

However, the UNPD projections can be compared with projections from the IIASA to get an indication of the order of magnitude of the probability of the used UNDP scenarios. The IIASA projections indicate a 14% chance that population will be below the low UNDP scenario and a 5% change that projection will be higher than the lowest (data estimated from graph)[29]. This gives an indication of the order of magnitude of the uncertainty of the high and low scenario. The UNPD simply states that it is very unlikely that future population numbers will fall without the range indicated by the low and high scenario. A comparison of different projections by the UNPD, IIASA and USCB is shown in figure 6. The medium projections are all based on independent assumptions (Lutz 2001), but the range in medium projections is limited (9.1 to 9.9 billion)[30]. The medium scenario is the most likely because the used values for the parameters (e.g. fertility, mortality) in the different scenarios on itself may be evenly probable but the counteracting effects of the combination of some parameters makes the medium scenario more likely.

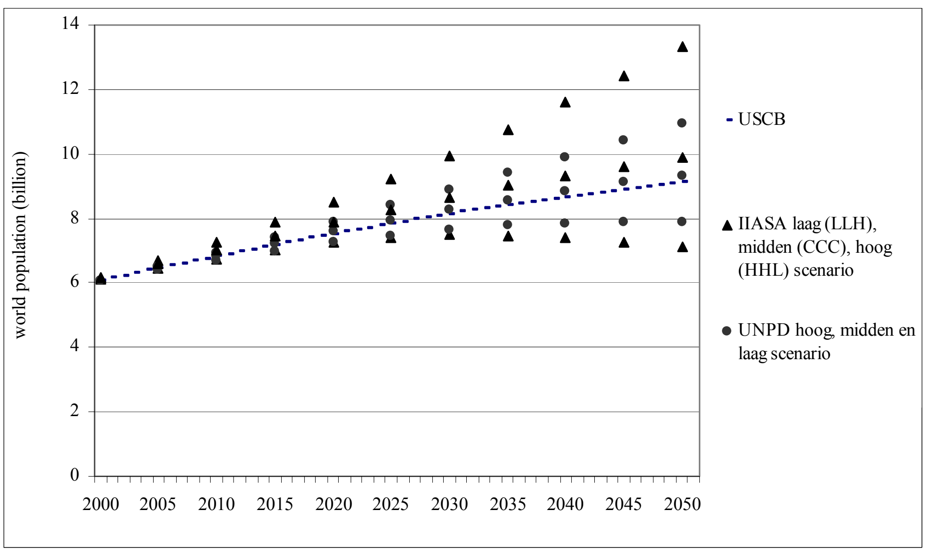


*Figure 6.* Comparison of population projections from different sources. Sources: (Lutz 1996; UNPD 2002; USCB 2002).

As can be seen in figure 6, the IIASA projections show the largest spread in population projections in 2050: between 7 and 13 billion people. Note that the UNDP and IIASA projections are not necessarily contradictive, since the projections may simply vary in the extend that they show results with is more or less probability. In a recent IIASA publications, the calculated probability of the different growth projections shows that a doubling of the world population or more in 2100 is unlikely (10% change) and that in 2050 the population will reach 7,3 to 10,9 billion in 2050 (95 percent interval). (Lutz 2001). Further, the population in the developed regions is expected to stabilize at the current level. The largest population increase will occur

[29] Population projections are based on different scenarios for parameters e.g. mortality, fertility, life expectancy etc. These parameters are influenced by income, level of education etc. but also influence these parameters. To what extend this problem leads to estimates is not known.

[30] To be able to compare the different projections, the data in figure 6 are based on a earlier versions of the UNPD and USCB projections. The population scenarios used in this study are based on the UNPD 2002 (UNPD 2003).

before 2030 and in the developing countries. The deceleration is demographic growth is one of the factors that slows down the growth of food demand and production.

Though the speed of growth rapidly decreases, measured in absolute numbers the world population continues to grow rapidly. The regional aggregated scenarios for population growth are summarized in table 3. The definition of regions is described in Appendix A and follows FAO classification.

*Table 3.* Population growth 1965 to 2050 for three scenarios (high, low and medium and constant fertility (million heads) Source: (UNPD 2003)

| Region | 1965 | 1975 | 1985 | 1995 | 2000 | 2050 medium | 2050 low | 2050 high | 2050 constant |
|---|---|---|---|---|---|---|---|---|---|
| West Africa | 86 | 112 | 149 | 196 | 226 | 570 | 482 | 667 | 1,109 |
| Central Africa | 30 | 39 | 52 | 72 | 80 | 222 | 189 | 258 | 401 |
| East Africa | 79 | 103 | 139 | 181 | 212 | 534 | 452 | 623 | 1,001 |
| Southern Africa | 55 | 70 | 90 | 116 | 133 | 228 | 188 | 272 | 405 |
| Central America | 58 | 78 | 100 | 123 | 135 | 211 | 171 | 258 | 316 |
| Caribbean | 20 | 24 | 28 | 32 | 33 | 41 | 33 | 49 | 54 |
| South America | 170 | 216 | 268 | 320 | 347 | 511 | 416 | 609 | 654 |
| North Africa | 63 | 80 | 104 | 130 | 142 | 245 | 200 | 296 | 357 |
| Near East | 99 | 132 | 162 | 230 | 258 | 542 | 453 | 641 | 846 |
| South-East Asia | 221 | 282 | 348 | 414 | 447 | 654 | 529 | 798 | 870 |
| East Asia | 811 | 1,033 | 1,196 | 1,370 | 1,430 | 1,607 | 1,306 | 1,962 | 1,660 |
| Northern South Asia | 126 | 164 | 217 | 276 | 304 | 654 | 543 | 779 | 1,222 |
| Southern South Asia | 506 | 634 | 784 | 952 | 1,036 | 1,553 | 1,259 | 1,897 | 2,476 |
| North America | 219 | 243 | 268 | 297 | 316 | 448 | 391 | 512 | 453 |
| Oceania | 14 | 17 | 19 | 22 | 23 | 30 | 27 | 33 | 30 |
| Japan | 99 | 112 | 121 | 125 | 127 | 110 | 101 | 120 | 105 |
| Western Europe | 341 | 360 | 370 | 384 | 389 | 380 | 339 | 424 | 359 |
| East Europe | 104 | 112 | 120 | 121 | 121 | 101 | 91 | 113 | 98 |
| C.I.S. and Baltic States | 231 | 254 | 277 | 291 | 290 | 242 | 209 | 279 | 269 |
| sub-Saharan Africa | 250 | 325 | 430 | 565 | 651 | 1,553 | 1,311 | 1,820 | 2,915 |
| Caribbean & Latin America | 247 | 318 | 397 | 475 | 515 | 763 | 620 | 917 | 1,025 |
| Near East & North Africa | 162 | 212 | 266 | 360 | 400 | 788 | 654 | 937 | 1,202 |
| East Asia | 1,032 | 1,315 | 1,544 | 1,784 | 1,877 | 2,262 | 1,835 | 2,761 | 2,530 |
| South Asia | 632 | 799 | 1,001 | 1,228 | 1,340 | 2,208 | 1,802 | 2,676 | 3,697 |
| World | 3,331 | 4,068 | 4,813 | 5,653 | 6,049 | 8,844 | 7,349 | 10,542 | 12,684 |

The data in table 3 show that the range in high and low population scenario is larger in the developing countries than in the developed world and transition. This indicates the presently high fertility rates, thus also a the possibility of strongly decreasing fertility rates often associated with high(er) levels of industrialization.

Further, the data shows significant increases in population in Oceania and North America (+35% and +47% respectively compared to the base year 1998 used in this study). Data with decreasing population are Japan, Western Europe, Eastern Europe, C.I.S. and the Baltic States (-13%, -2%, - 16%, - 17% respectively). The difference between the high and low population scenarios for the developing regions indicates a variation of roughly plus or minus 30% to 40% (medium projection, with the exception of East Asia: -20% for the low population scenario). The variation for the developed regions is roughly between +/-10% (with exception of North America: +/-20%

high growth scenario and Oceania: +/-15%). The strongest population growth can be expected in sub-Saharan Africa (+150% to 230% increase).

## APPENDIX F

## OVERVIEW OF PROJECTIONS FOR THE DEMAND OF INDUSTRIAL ROUNDWOOD TO 2050

*Table 4.* Projected demand for industrial roundwood found in literature (million $m^3$). Source: Supplemented and modified from (Weiner 2000).

| Source | mid 90's | 2000 | 2010 | 2020 | 2050 |
|---|---|---|---|---|---|
| (Apsey and Reed 1995) | | 1790 | 1940 | 2250 | |
| (Brooks *et al.* 1996) scenario #1 | | 1730 | 1840 | | |
| (Brooks *et al.* 1996) scenario #2 | | 1780 | 1980 | | |
| (Brown *et al.* 1999) | 1493 | | 1881 | | |
| (FAO 1995a) | | 1900 | 2280 | | |
| (FAO 1999) | 1490 | | 1872 | | |
| (FAO 1997b) | 1475 | 1627 | 1784 | | |
| (FAO 2002a) | 1513 | 1588 | | | |
| (GTM 1998) | | 1800 | | | |
| (IIED 1996) | 1784 | 1878 | 2046 | 2177 | |
| (ITTO 1999) | | 1995 | 2166 | 2260 | |
| (Poyry 1995) | | 1500 | 1700 | | |
| (Nilsson 1996) | | | 2100 | 2400 | |
| (Nilsson 1996), non-mainstream | | 1730 | 1890 | | |
| (RFF 1998) base case | | 1700 | | | |
| (RFF 1998) high demand | | 1800 | | | |
| (Sedjo 1990) | | 1810 | 1970 | | |
| (Sohngen 1997) high demand | | | | | 2500 |
| (Sohngen 1997) low access cost | | | | | 2200 |
| (Sohngen 1997) baseline | | | | | 2100 |
| (Sohngen 1997) low plantation | | | | | 2000 |
| (Sohngen 1997) low demand | | | | | 1850 |
| (Solberg 1996) scenario 1 | | 1730 | 1840 | 1870 | 1880 |
| (Solberg 1996) scenario 2 | | 1730 | 1860 | 1910 | 1970 |
| (Solberg 1996) scenario 3 | | 1780 | 1980 | 2120 | 2450 |
| (Solberg 1996) scenario 4 | | 1780 | 2000 | 2150 | 2570 |
| (Solberg 1996) scenario 5 | | 1810 | 2080 | 2290 | 2930 |
| (Solberg 1996) scenario 6 | | 1810 | 2090 | 2330 | 3070 |
| World Bank/WWF Alliance (unpublished) in (Weiner 2000) | 1500 | | | | 3000 |
| (WRI 1998) | | | 1907 | 2251 | |
| IMAGE A1 scenario[31] (IMAGE-team 2001) | 1505 | 1634 | 2022 | 2511 | 5014 |
| IMAGE A2 scenario (IMAGE-team 2001) | 1505 | 1632 | 1877 | 2095 | 2852 |
| IMAGE B1 scenario (IMAGE-team 2001) | 1505 | 1633 | 1778 | 1896 | 2341 |
| IMAGE B2 scenario (IMAGE-team 2001) | 1505 | 1634 | 1911 | 2186 | 2844 |
| (Bazett 2000) | | | | | 2500 |
| (Alexandratos 1994) | | | 2700 | | |
| (FAO 2003b) | 1513 | | | 2400 | |
| Trend extrapolation of (FAO 2003b) | | | | | 3218 |
| (FAO 2000c) scenario 1 | | | | | 3100 |
| (FAO 2000c) scenario 2 | | | | | 2900 |
| (FAO 2000c) scenario 3 | | | | | 2340 |
| Population growth only (constant per capita consumption) | | | 1762 | | |

The figure given by the IMAGE-team for the consumption of is clearly based on specific scenario assumptions that increase wood consumption. All Image scenarios are considered equally likely,

[31] This figure is based on a *scenario*, rather than an assessment of a *most likely future*. Although all IMAGE scenarios are considered likely-possible, the range projected by other authors suggests that this level of consumption falls out of the range of 'most likely' level of consumption. This figure is further left out of this analysis.

but considering the range projected by other authors suggests that this level of consumption falls out of the range of 'most likely' level of consumption. The IMAGE A1 wood consumption is therefore not included in out analysis.

The scenarios on future wood consumption are clearly hindered by a clear picture on the current demand and supply situation and the supply-demand dynamics. Plantations supply some ca. 35% of the global roundwood supply (FAO 2001). The remaining comes from old-growth forests and secondary forests (forests which have been cut down but have regrown). Detailed data on the proportions coming from both are not available (WRI 1999). The contribution of e.g. deforestation *in theory* accounts half of the global wood demand (based on 0.24% rate of deforestation and an average standing volume of 95 $m^3$ per hectare (FAO 2001, 2002a) of which 83% commercial species (FAO 2001)).

Further, studies also differ in the basic assumption on key-issues such as economic growth, change in prices and rates of technological change. Even with consensus on these assumption, outlook studies still differ in their methods and their objective. Some studies are intended to describe the impact of a policy measure or focus on a specific market process; 'gap' studies are intended to indicate a discrepancy between supply and demand, while equilibrium model this interaction is specifically included (Brooks 1997). Further, the different consumption projections may differ in assumed rates of deforestation for agriculture.

## INDUSTRIAL ROUNDWOOD CONSUMPTION SCENARIOS

*Table 5*. Consumption of industrial roundwood in 1998 and 2050 (three scenarios; million $m^3$).

| Region | Industrial roundwood (excl. other industrial roundwood) | | | | Other industrial roundwood | | | |
|---|---|---|---|---|---|---|---|---|
| | 1998 | 2050 low | 2050 medium | 2050 high | 1998 | 2050 low | 2050 medium | 2050 high |
| North America | 611 | 801 | 980 | 1,261 | 18 | 15 | 14 | 13 |
| Oceania | 22 | 36 | 60 | 86 | 1 | 1 | 1 | 1 |
| Japan | 75 | 109 | 140 | 189 | 1 | 0 | 0 | 0 |
| Western Europe | 260 | 312 | 371 | 456 | 6 | 6 | 5 | 5 |
| East Europe | 48 | 54 | 61 | 71 | 7 | 6 | 6 | 5 |
| C.I.S. and Baltic States | 113 | 144 | 156 | 167 | 33 | 29 | 27 | 26 |
| sub-Saharan Africa | 32 | 35 | 34 | 33 | 28 | 39 | 49 | 65 |
| Caribbean & Latin America | 117 | 122 | 118 | 114 | 13 | 19 | 24 | 32 |
| Near East & North Africa | 13 | 17 | 20 | 25 | 9 | 13 | 17 | 23 |
| East Asia | 162 | 204 | 246 | 310 | 57 | 87 | 114 | 159 |
| South Asia | 38 | 40 | 45 | 53 | 7 | 10 | 13 | 17 |
| World | 1,491 | 1,874 | 2,230 | 2,761 | 181 | 226 | 270 | 339 |

The data given in table 5 should be considered as guestimates only. The higher the level of regional aggregation, the more reliable because of the use of the flattening and cancelling out of underlying flaws resulting from the trend extrapolation, premature nature of the dataset and the use of the dataset primarily as allocation tool.

## ROUNDWOOD CONVERSION FACTORS

*Table 6.* Regional average roundwood conversion factors. Source: (FAO 2003a).

| Region | Roundwood to | | | | | |
|---|---|---|---|---|---|---|
| | Sawn-wood | Pulp-wood | Particle Board | Fibre Board | Mechanical pulp | Chemical pulp |
| North America | 1.51 | 1.80 | 1.50 | 1.60 | 2.50 | 3.50 |
| Oceania | 1.51 | 1.90 | 1.30 | 1.35 | 2.25 | 3.25 |
| Japan | 1.50 | 1.80 | 1.20 | 1.20 | 2.00 | 2.90 |
| Western Europe | 1.63 | 1.90 | 1.40 | 1.47 | 2.38 | 3.12 |
| East Europe | 2.10 | 2.34 | 1.77 | 1.89 | 2.97 | 4.16 |
| C.I.S. and Baltic States | 2.23 | 2.47 | 1.85 | 1.98 | 3.10 | 4.34 |
| sub-Saharan Africa | 2.54 | 2.73 | 1.66 | 1.87 | 2.99 | 4.00 |
| Caribbean & Latin America | 2.32 | 2.56 | 1.90 | 2.09 | 3.57 | 4.67 |
| Near East & North Africa | 2.08 | 2.25 | 1.61 | 1.75 | 3.37 | 4.43 |
| East Asia | 1.97 | 2.12 | 1.58 | 1.68 | 3.51 | 4.57 |
| South Asia (data for India only) | 1.60 | 2.00 | 1.50 | 1.60 | 3.00 | 4.00 |
| World | 2.16 | 2.38 | 1.67 | 1.82 | 3.12 | 4.17 |

The conversion efficiencies are not measured figures rather calculated estimates for modelling. The conversion efficiencies are regional non-weighed averages. Note that the actual available amount of residues varies widely due to other uses as e.g. fuel, soil improver, fertilizers.

## APPENDIX G

## OVERVIEW AND DESCRIPTION OF PROJECTIONS OF FUELWOOD CONSUMPTION TO 2050

*Table 7.* Range of future demand for fuelwood as found in literature (million $m^3$).

| Source | 1990's | 2000 | 2010 | 2020 | 2050 |
|---|---|---|---|---|---|
| (Apsey and Reed 1995) | | | 2310 | | |
| (FAO 1995b) | 1940 | 2090 | 2380 | | |
| (Zuidema 1994) | | | 1500 | | |
| (Nilsson 1996) | | 3800 | 4250 | | |
| (Solberg 1996) scenario 1 | | 1900 | 1980 | 2030 | 2100 |
| (Solberg 1996) scenario 2 | | 1900 | 1940 | 1930 | 1860 |
| Solomon in (Nilsson 1996) | | | 2520 | 2920 | |
| IMAGE A1 (IMAGE-team 2001) | 1789 | 1874 | 1997 | 2053 | 1954 |
| IMAGE A2 (IMAGE-team 2001) | 1789 | 1887 | 2121 | 2306 | 2480 |
| IMAGE B1 (IMAGE-team 2001) | 1789 | 1876 | 1987 | 1937 | 1734 |
| IMAGE B2 (IMAGE-team 2001) | 1789 | 1858 | 1933 | 1961 | 1768 |
| (Alexandratos 1994) | | | 2400 | | |
| (FAO 2003b) | 1778 | 1828 | 2020 | 2272[32] | |
| Trend extrapolation of (FAO 2003b) | | | | 3177 | |
| Population growth only (constant p.c. consumption) | | | | 2790 | |

In developing countries ca. 80% of all harvested wood is used as primary fuel by 2 billion people, which adds up to 15% of their total energy use (EFI 1996). Despite this importance, projections for fuelwood consumption are hindered by a lack of reliable and detailed data on the current demand and supply situation. Published data for fuelwood are based largely on estimates and this uncertainty is also visible in the projections for fuelwood consumption (Brooks *et al.* 1996). The FAO indicates that to 2015 it there is unlikely that any significant change in the growth rate fuelwood consumption will occur (FAO 2003b). Projections given by Apsey and Reed (Apsey and Reed 1995) are based on higher estimates on present fuelwood consumption and consequently project a much higher fuelwood consumption for 2010 up to 4.3 billion $m^3$. The high figures of Nilsson are based on calculations of the basic requirements for fuelwood necessary to achieve development objectives (Nilsson 1996).The relatively low fuelwood consumption levels projected by the IMAGE model can be explained by the relatively strong increase in GDP and diminishing income gaps. The World Bank GDP projections on which the FAO projections are based indicate much slower increase in GDP and much slower closing, if not widening, differences in income (see Appendix P). Projections by Zuidema *et al.* (1994) are based on the IMAGE model and include large land use and vegetation changes due to the greenhouse effect, resulting in a projected fuelwood consumption of 1,5 billion $m^3$.

## SOURCES OF FUELWOOD

Because of the highly dispersed way of fuelwood gathering and production a clear view on the present sources of fuelwood supply is uncertain (Brooks *et al.* 1996). Wood fuel plantations (non-industrial) supply some 12% of the remaining global wood fuel demand. Recent data suggest that significant amounts of fuelwood comes from trees outside the forest. For the Asian-Pacific region this is estimated to be two-thirds of the total consumption (FAO 1998a) with country specific data ranging from 50 to 85% (Jensen 1995). Agro forestry and orchards provide a large part of the

[32] Based on 2585 million $m^3$ in 2030.

resource in that region. The Renewables Energy Database provides country specific data on fuelwood from forests: 83% in Bangladesh, India 17%, Indonesia 15%, Nepal 66%, Philippines 10% and Vietnam 18%. In small urban areas of Asia and Africa where biomass supplies 50 to 90 percent of the domestic energy need, a fairly substantial proportion of the wood is gathered inside the towns (Kuchelmeister 2000). In Africa fuelwood production is more commercialised and the figure of two-third is likely an overestimation of the fuelwood from non-forest resources (A. Whiteman, pers.comm, FAO, July 2003).

Due to a lack of more detailed data the figure of two-thirds of the total fuelwood demand was used to calculate non-forest wood sources in the developing countries to calculate the demand of fuelwood from forests and plantation resources. It is often mentioned that fuelwood gathering (twigs, small branches and other forest residues such as uncommercial species) contributes significantly to the fuelwood supply. These sources can be derived from the forests without serious damage and are partially an explanation of the reason that the projected fuelwood crises did not occur. Due to a lack of data and to prevent overestimation of the bioenergy production potential this was not included. For the industrialized countries and the transition economies we assumed that 25% of all fuelwood comes from trees outside the forest.

## APPENDIX H

### LAND SUITABILITY CLASSIFICATION

The Excel model used to allocated the demand for food crops (including the demand for feed crops) is based on crop specific datasets and one dataset that represent the total area where crop production is possible. The datasets classify soils according to five different suitability levels very suitable (VS), suitable (S), moderately suitable (MS), marginally suitable (mS) and not suitable (NS). The suitability classes are defined based on percentage of the maximum constraint free (temperature and radiation limited) yield (MCFY). VS areas provide 80 to 100% of the MCFY , S areas 60-80%, MS 40-60%, mS 20-40 and NS 0-20%. Land classified as not suitable is sometimes used for rain fed agriculture in several countries, e.g. where steep land has been terraced or where yields less than the maximum constrained free yield are acceptable under the local economic and social conditions (FAO 2000b).

### THE CALCULATION OF THE TOTAL EXTEND OF SUITABLE CROPLAND

The original data on area and yields are based on a crop growth model that uses georeferenced datasets on climate, soil quality etc. (FAO 2000b). The Excel datasets are subtracted from this Geographic Information Systems using a specific calculation procedure.

The calculation of the yield-area combinations for each crop in a low, medium and high level of technology are based on the percentage of the MCFY of each grid cell. This means that the total area suitable (VS to mS) for crop growth can decrease or increase if e.g. more technologically advanced management system is applied. A decrease is possible when the MCFY increases due to e.g. the use of better varieties but the achievable yield remains stable because it is limited by natural circumstances that fall out of the influence of the management system. In such situations, an area previously classified as e.g. mS is now classified as NS.

The calculation of the total area suitable for 'general' crop production is based on a combination of crop specific datasets. The calculation procedure is that first the crop with the largest extend S and VS (excluding fodder crops and grasses) is determined for each grid cell. The area VS in this grid cell is than the area VS in the 'general' crop productivity dataset. The same has been done to determine the areas S, MS and mS.

The calculation of the mixed input system is based on the following calculation steps (FAO 2000b):

1. determine all land very suitable and suitable at high level of inputs;
2. of the balance of land after 1, determine all land very suitable, suitable or moderately suitable at medium level of inputs, and
3. of the balance of land after 1 and 2, determine all suitable land (i.e. very suitable, suitable, moderately or marginally suitable land) at low level of inputs.

## APPENDIX I

### FEED CONVERSION CALCULATION METHODS

In this study five animal production systems are analysed:

- cattle meat
- milk
- mutton & goat meat
- pig meat
- poultry meat and eggs.

Further, five types of feed are included.

- pastures & fodder crops
- agricultural residues & wastes
- feed crops
- feed from scavenging
- animal products

Globally, 47% of all biomass inputs in the animal production system comes from pastures, 13% from cereals feed, 12% from fodder crops, 25% from wastes and by-products and 2,4% cropland pastures (Wirsenius 2000). FAO data indicate that in all regions the use of animal products is below 1% of the dry weight. The use of animal products other than the use of milk and eggs for reproduction is therefore excluded from this study.

The feed conversion efficiency (f.c.e.) is in this study defined as the ratio fresh weight production of biomass to dry weight biomass input of feed. F.c.e. data can be calculated based on a input – output top-down analysis, dividing the biomass inputs by the output (per production system). This approach however, is hampered by the limited availability of statistical data on the biomass inputs in the animal production system. Data on permanent pastures are generally only available in areas, not for the actual biomass subtracted from pastures through grazing. Data on the use of agricultural residues, wastes, and feed from scavenging are not available, because these biomass flows often never enter the commercial market and are therefore not statistically monitored. Only a theoretical amount of harvesting and processing residues can be calculated, but this shift the problem to estimates of a realistically percentage used. For feed and fodder data are available from the FAOSTAT database (FAO 2002a).

Consequently, data on the actual biomass turnover in the animal production system are very limited, especially for the different animal sub-systems (FAO 1996). Detailed data on the output of the animal production system are readily and detailed available at the country level from statistics such as FAOSTAT (FAO 2002a).

Considering the complexity of the animal production system and the many biomass flows involved, we did no attempt to calculate feed efficiencies. Instead, data from the IMAGE model were used. The datasets are estimates, but are – as stated in a different report with similar feed conversion efficiencies '*reasonable reliable for regions with relative uniform intensive systems, but may be less reliable where a variety of less intensive systems are also included'*. These uniform intensive systems basically refer to the production of pig meat, poultry meat and eggs. These production systems are based mainly on concentrated feed for which statistics are available. Variation in the calculated feed conversion efficiencies between both regions and studies are consequently much smaller than for bovine meat, milk and mutton & goat production systems, indicating a higher reliability. Additional complicating factors are that the production of bovine meat, milk and mutton and goat use is partially based on pastures for which no biomass production statistics are available (globally half of the biomass inputs in the animal feed production system). Further, in the developing regions livestock is kept as a means of storing wealth, without consideration of their productive value and livestock is also kept for different purposes such as ploughing and milk and or meat production.

For reasons described above it was not possible to calculate the feed conversion efficiencies ourselves. Data on feed conversion efficiencies are based on a study on feed conversion efficiencies on behalf of the IMAGE model (Bouwman *et al.* 2003). Data were obtained via the IMAGE-team and were translated into the regional aggregation used in this study. We are aware that this introduces errors due to differences in regional aggregation. In addition, a low, medium and high conversion efficiency was taken to reflect the impact of technology. The low and high feed conversion efficiencies are based on the feed conversion efficiencies in the developing countries and developed countries respectively. The medium feed conversion efficiency is the average of the two.

## COMPARISON OF FEED CONVERSION EFFICIENCY DATA

Table 8 shows feed conversion efficiencies expressed as kg dry matter intake per kg fresh weight animal products from two sources. The data are meant to indicate the variation and uncertainty related to f.c.e. data and are used to discuss the characteristics of various animal production systems.

*Table 8.* Feed conversion efficiencies (“ indicates that data are the same as in the row above means same as above (or below in case when no data are shown above) due to lack of regional detailed data; w.av. = weighed average). Sources: (FAO 1996; IMAGE-team 2001).

| kg dry matter intake/ kg product | Bovine meat | | | Pig meat | | |
|---|---|---|---|---|---|---|
| Region | FAO w.av. | FAO min.-max. | IMAGE | FAO w.av. | FAO min.-max. | IMAGE |
| North America | “ | " | 27 | " | " | 6.2 |
| Oceania | “ | " | 35 | " | " | 6.2 |
| Japan | 21 | 12-30 | 20 | 5.12 | 5.1-5.6 | 6.2 |
| West Europe | " | " | 24 | " | " | 6.2 |
| East Europe | 25 | 15-41 | 22 | 5.4 | 5.4-5.6 | 7 |
| CIS & Baltic States | " | " | 22 | " | " | 7.36 |
| sub-Saharan Africa | 55 | 41-123 | 87 | 6.2 | 6.0-6.3 | 6.6 |
| Central and South America | 12 | 6-42 | 60 | 5.72 | 5.6-5.9 | 6.6 |
| North Africa & Middle East | 63 | 31-101 | 36 | 5.68 | 5.6-5.9 | 7.5 |
| East Asia | 51 | 17(?)-72 | 71 | 5.74 | 5.6-5.9 | 6.96 |
| South Asia | " | " | 72 | " | " | 6.6 |
| Other Developed | 34 | 9-43 | - | 5.5 | 5.4-5.6 | - |
| World | 33 | 12-123 | 45 | 5.46 | 5.1-6.3 | 6.74 |

Table 8 continued

| kg dry matter intake/ kg product<br>Region | Poultry meat<br>FAO w.av. | <br>FAO min.-max. | Eggs<br>FAO w.av. | <br>FAO min.-max. | Milk<br>FAO w.av. | <br>FAO min.-max. | <br>IMAGE |
|---|---|---|---|---|---|---|---|
| North America | " | " | " | " | " | " | 0.96 |
| Oceania | " | " | " | " | " | " | 1.10 |
| Japan | 2.97 | 2.9-3.9 | 2.84 | 2.8-3.3 | 1.20 | 0.7-1.9 | 1.13 |
| West Europe | " | " | " | " | " | " | 1.04 |
| East Europe | 3.31 | 3.1-4.3 | 3.17 | 3-4.1 | 2.40 | 2.4-2.9 | 1.17 |
| CIS & Baltic States | " | " | " | " | " | " | 1.40 |
| sub-Saharan Africa | 4.23 | 3.6-4.8 | 4.33 | 3.7-5 | 7.60 | 5.7-13.8 | 3.16 |
| Central and South America | 3.54 | 3.3-4.3 | 3.57 | 3.4-4.4 | 3.40 | 1.1-4.2 | 2.64 |
| North Africa & Middle East | 3.42 | 3.1-4.3 | 3.53 | 3.2-4.4 | 3.30 | 1.1-14.5 | 1.53 |
| East Asia | 3.79 | 3.3-4.3 | 3.75 | 3.5-4.4 | 3.40 | 2.8-10.9 | 2.05 |
| South Asia | " | " | " | " | " | " | 1.73 |
| Other Developed | 3.41 | 3.1-4.3 | 3.2 | 2.9-4.1 | 1.50 | 0.6-1.9 | - |
| World | 3.29 | 2.9-4.8 | 3.35 | 2.9-5 | 0.50 | 0.6-14.5 | 1.57 |

These data match roughly with feed conversion efficiencies included in the IMAGE model (note that the IMAGE data shown in table 8 are based on a previous version of the IMAGE model; the data included in this study are based on a newer dataset. The second dataset included is based on different datasets from the FAO report (FAO 1996). The calculated data are the weighed averages from data specific for 8 different production systems that differ in agroecological zone and the origin of input (pastoral or mixed). Data included are the number of animals, average live weight, feed demand per kg live weight and production per production system. The regional breakdown used in the FAO study includes 7 regions. These datasets however, are less detailed than the IMAGE data which could be at least partially explain differences.

The IMAGE data indicate slightly lower efficiency of feed conversion than the calculated FAO data. For pig meat these are: 6,2 for the industrialised world, 7,0 to 7,4 for EE and C.I.S. & Baltic states and 6,6 to 7,5 for the developing regions. Grazing production systems are not relevant for pig meat production. FAO data indicate that the highest efficiency in each region is achieved in intensive production systems (mixed irrigated systems with feed crops from irrigated lands and landless production systems where feed is introduced from outside the farm). Other validations are difficult, because of a lack of studies that include regional averages and due to differences in classification.

For poultry meat and egg production, the highest feed conversion efficiencies are achieved in industrialised production systems. Feed conversion efficiencies are at least 0,5 kg dw $kg^{-1}$ lower than in other production systems (- ca.15%). This type of production accounts for 74% of poultry and 68% of egg production (FAO 1996). However, based on the differences in both current and maximum feed conversion efficiencies in the industrialised countries and in the developing regions, there remains a large potential for improvement. The lowest feed conversion efficiency is applicable for grassland based production systems which only relevant for sub-Saharan Africa where it accounts for one fourth of the poultry and egg consumption.

The conversion efficiencies for milk, beef and veal production and mutton & goat are show a larger variation. The data derived from the different FAO datasets show some intuitively very large and some unlikely regional differences[33]. The regional level of detail is further limited by the use of the same feed demand data for the regions South America, Asia and Africa. Expert consultation revealed that especially for these production systems such differences may very well reflect the difficulties and uncertainties related to these calculations.

## FEED CONSUMPTION SCENARIOS

Differences in feed conversion efficiencies are the result of the cumulative effect of various parameters:

- the structure of the animal population
- the type of animal breed used
- the level of animal health care
- the composition of the animal feed

The composition of the animal feed is an important factor for several reasons. The quality of feed (nutritional value of which proteins are the most important) varies greatly; one ton of pasture biomass has a HHV of 17.5 GJ $ton^{-1}$ dw and 15% protein content, oilcrops biomass has a HHV of 23.4 GJ $ton^{-1}$ and 40% protein content. Due to a lack of more detailed feed demand data this aspect is not further included. Note that an analysis of the feed conversion efficiencies and feed composition reveals that the impact of feed composition is largely overwhelmed by other factors. From a land use perspective however, the impact is very large because feed intake from grazing and scavenging which is a relatively inefficient way of feed collection; theoretical efficiency gains from changing from grazing to landless systems are large. Grazing also reduces the possibility of optimising other management aspects such as the type of breed, disease control used.

The following animal feed resources and datasets used are included in this study:

- *Feed crops:* includes all cereals, roots and tubers, sugar crops, oilcrops and vegetables and fruit used for feed, but which are not specifically grown for feed. The FAOSTAT database includes country specific data on the production, import and export (FAO 2002a). The relative increase in feed consumption is calculated based on the scenarios for feed conversion efficiency and type of production system(s) used. The feed intake is calculated based on the feed demand in the base year (1998) and the relative change, thereby assuming a constant feed composition. The land use for feed production is included in the land use allocation model.
- *Fodder:* the data on conversion efficiency, feed composition and production system allow a calculation of the fodder and feed demand. Fodder consumption is aggregated with pastures (both the areas and total demand). Data on areas fodder are derived from the FAO database (FAO 2002a) and are summed up with pasture areas.
- *Pastures:* data on total area pasture is available at a country basis, but were regionally aggregated (FAO 2002a) and summed up with the areas fodder. A global (regionally aggregated) dataset of measurements of the actual pasture biomass use in the animal production system is not existent. Existing data on pasture biomass use are derived from the calculated feed requirements, production of animal products, the number of animals etc. and may be considered as rather uncertain. The relative increase in pasture and fodder biomass is

[33] In general, calculated FAO feed conversion efficiencies are lower for milk, but lower for higher for bovine meat. This difference would be even larger when dual purpose cattle would have been (partially or completely) allocated in our calculations to the milk production system instead of beef and veal production. Mutton and goat production efficiencies showed mixed and very large differences with IMAGE data.

calculated (this actually is a grazing intensity or increase in fodder production). To what extend this increase can be produced can not be estimated, but alternatively, the pasture and fodder production is assumed constant and additional pasture and fodder demand comes from feed crops or all pasture and fodder feed demand comes from feed crops.

- *By-products and residues:* includes both harvest and processing residues: the theoretical available amount of by-products can be calculated based on conversion efficiencies and harvest indexes. Especially the harvest index varies significantly with the level of technology applied. For both a high, medium and low efficiency scenario is composed, in line with the agricultural efficiency used in the land allocation model. The total calculated demand for by-products and residues is subtracted from the total available amount of by-products and residues.
- *Feed from scavenging:* data on feed from scavenging are not available in any database and are mere questimates, but derived from the feed conversion efficiency data. The data on feed conversion efficiency, food composition and production system include data on feed composition, also for scavenging expressed a percentage of the total feed demand. No land use is allocated to feed from scavenging.

The issue of feed composition is less relevant for pigs and poultry, because feed inputs are more homogenous and production systems are completely landless (meaning that not pastureland is being used). For the milk and beef production systems, there are large differences in feed conversion efficiency between are partially the result of the production system. Consequently, the feed conversion efficiencies are partially inherent due to differences in the natural resource base available in a region, notably the occurrence of *natural* pastures.

Therefore, when calculating a land use for animal products, changes in the resource base translate into changing feed conversion efficiencies. Similarly, changes in feed conversion efficiency require (partially) changes in the type of biomass. Following the argumentation above, the range in future efficiencies will narrow and end very close if not the same for pigs, poultry and eggs production. For milk, bovine and meat and milk production, these efficiencies are also much dependant on the natural resource base, since grazing systems are usually less efficient than mixed production system (Bouwman *et al.* 2003). Globally, 52% of the feed for bovine animals comes from grazing.

The IMAGE data includes data on the present and future feed composition. For the low, medium and high feed conversion data, feed composition is based on guestimates of the feed composition under which such feed conversion efficiency could become reality (as present in the industrialised countries for the high feed conversion scenario and as present in the developing regions for the low feed conversion efficiency). Because of the overwhelming impact of other factors on feed conversion efficiency, feed composition data were only changed when clearly a certain feed composition was required. This has been done in the following instances:

- Mixed production system:
  - high feed conversion efficiency scenario. Non-dairy and dairy production system: 50% grazing biomass, 0% scavenging, 20% residues and 30% feed. Pig meat and poultry production system: 0% grazing, 25% residues, 0% scavenging and 75% feed. Mutton and goat meat: 85% grazing biomass, 5% residues, 0% scavenging, 10% feed.
  - low feed conversion efficiency scenario. Non-dairy and dairy production system: 60% grazing biomass, 5% scavenging, 30% residues and 5% feed. Pig meat and poultry production system: 0% grazing, 25% residues, 0% scavenging and 75% feed. Mutton and goat meat: 90% grazing, 5% grazing biomass, 5% residues and 0% feed.
- Pastoral production system:

    - high feed conversion efficiency scenario. Non-dairy and dairy production system: 95% grazing biomass, 0% scavenging, 0% residues and 5% feed. Mutton and goat meat: 95% grazing biomass, 5% residues, 0% scavenging, 0% feed.
    - low feed conversion efficiency scenario. Non-dairy and dairy production system: 95% grazing biomass, 5% scavenging, 0% residues and 0% feed. Mutton and goat meat: 95% grazing biomass, 5% scavenging, 0% residues, 0% feed.
- Landless production system:
    - high feed conversion efficiency scenario. Non-dairy and dairy production system: 20% residues and 80% feed. Pig meat and poultry production system: 25% residues and 75% feed. Mutton and goat meat: 5% residues and 95% feed.
    - low feed conversion efficiency. A low feed conversion efficiency in combination with a landless (industrialised) production system is considered unlogical and therefor not included.

## APPENDIX J

## THE PRODUCTION OF (FUEL)WOOD FROM PLANTATIONS TO 2050

Whenever our calculations indicate a theoretical gap, this is considered to indicate that wood as a source for bioenergy are not available, if the sustainability criteria are applied.

In theory, the world could provide 21,4 billion $m^3$ industrial roundwood per year from natural forests (thirteen times the 1998 level of consumption) (EFI 1996). Despite this, industrial forest plantations supply some ca. 35% of the global roundwood supply (FAO 2001). Non-industrial forest plantations are mainly grown for wood fuel or soil and water protection and supply ca. 5% of the global fuelwood consumption, the remaining industrial roundwood comes mainly from natural forests (FAO 2000c). Natural forests are likely to remain an important source for industrial roundwood, but plantations are gaining importance rapidly.

In 2000 the FAO finished a study that included three scenarios on the future of plantation development (FAO 2000c). All three scenarios are included in this study:

- low scenario is based on the 1995 plantation area .
- medium growth scenario is the average of the low and high growth scenario.
- high growth scenario assumes a gradual reduction from current actual afforestation rates resulting in a industrial plantation area of 234 million (284 million ha assuming a similar increase in non-industrial plantation establishment). New planting rates are based on annual rates of new planting in tropical and subtropical countries from (Pandrey, 1997 in (FAO 2000c); for temperate countries new planting rates were estimated. For the period 2005-2050 these planting rates are reduced to 20% of the current new planting rate. The FAO states that the amount of planting required under scenario 3 represents the upper boundary of new planting rates and would require a significant change in current thinking about ecology and desired forest practices. This scenario seems to be achievable in physical terms. At the current annual rate of planting of 4,5 million ha this scenario could become reality in 2025 (assuming similar growth scenario for non-industrial plantations).

For both scenarios data on the future wood production per country in 2050 (FAO 2000c) were included in the calculations. This analysis does not include a number of varieties which could influence the real long term wood supply, but the data used the bioenergy potential:

- Both scenarios assume that all current plantation areas are replanted. It is also assumed that the species mix remains constant in present and future plantation establishment.
- Due to the skewed age structure of standing trees, wood production from plantations can show large variations without increasing or decreasing plantation area. Plantations established after 2025 will have little or no effect on the total wood supply in 2050. At this moment 54% of the industrial plantations are less than 15 years old. As a result of this skewed age structure, the production of wood from plantations established in 1995 or before is expected to grow from 536 to 776 million $m^3$ in 2050. The production data included in this report are based on the age structure and production levels of 2050 as provided by the FAO.
- Despite very promising results, plantations are not always as successful as expected. Only one third of the plantations established is successful (FAO 2001). The areas refer to the net plantation establishment, assuming that areas where plantation establishment has failed, are being used for agriculture or forest regrowth. Further, there are concerns that especially plantations with high-yielding species can not maintain long-term yields, e.g. because of water requirements for plantation establishment and soil erosion.

- In temperate and boreal zones the limiting factor in forest plantations is temperature and the length of the growing season. In these regions there is little scope to significantly increase yields, also because plantations are already fairly well managed. The present high variation in plantation yields in the tropical and subtropical zone suggest that there is a considerable potential to increase yields. In theory, the total wood demand could be met by 120% on the current plantation area and an annual yield of 15 $m^3y^{-1}$. Advances in genetic engineering, efficiency of irrigation and plant breeding are an other potential source of yield improvement, although improving matching of species to sites, improvements in plant storage, handling and planting, site preparation and soil improvement, pruning and thinning are likely to have a larger impact.

## APPENDIX K

## ESTIMATES OF BUILD-UP LAND

*Table 9.* Estimates of areas build-up land found in literature.

| Country / region | Area per capita (ha/cap) | Source |
|---|---|---|
| U.S.A. | 0.060 | (Wagonner 1994) |
| New England, U.S.A. | 0.025 | Spaulding and Heady, 1977 in (Wagonner 1994) |
| Mid-Atlantic, U.S.A. | 0.030 | Spaulding and Heady, 1977 in (Wagonner 1994) |
| U.S.A. | 0.143[34] | (EPA 2003) |
| New Zealand | 0.078 | Zarka, 1981 in (Wagonner 1994) |
| Colombia | 0.080 | Zarka, 1981 in (Wagonner 1994) |
| Uganda | 0.080 | Zarka, 1981 in (Wagonner 1994) |
| Bangladesh | 0.018 | FAO/UNPD, 1981 in (Wagonner 1994) |
| Developing countries | 0.021 | (Alexandratos 1994) |
| China | 0.028 | (Prosterman 1996) |
| China | 0.015-0.028 | (Ash 1998) |
| Netherlands | 0.023 | (CBS 2003) |

*Table 10.* Areas build up land used in this study. Source: (FAO 2002b).

| Region | Area per capita[35] (ha/cap) | Total build-up area (% of total land) |
|---|---|---|
| West Africa | 0.035 | 1.1 |
| Central-Africa | 0.048 | 0.7 |
| East-Africa | 0.040 | 1.2 |
| Southern-Africa | 0.042 | 0.8 |
| Central America | 0.031 | 1.6 |
| Caribbean | 0.024 | 1.5 |
| South-America | 0.036 | 0.7 |
| North Africa | 0.027 | 0.6 |
| Near East | 0.040 | 1.4 |
| South-East Asia | 0.027 | 2.4 |
| East Asia | 0.023 | 2.8 |
| Northern South Asia | 0.021 | 5.2 |
| Sountern South Asia | 0.021 | 6.4 |
| North America | 0.029 | 0.4 |
| Oceania | 0.029 | 0.1 |
| Japan | 0.020 | 6.6 |
| Western Europe | 0.026 | 2.7 |
| East Europe | 0.033 | 3.4 |
| C.I.S. and Baltic States | 0.034 | 0.4 |
| sub-Saharan Africa | 0.040 | 0.9 |
| Caribbean & Latin America | 0.034 | 0.8 |
| Near East & North Africa | 0.036 | 1.1 |
| East Asia | 0.024 | 2.7 |

[34] Based on 98million acres and 274 million people (EPA, 2003).
[35] Based on the 1995 UNPD population data (UNPD, 2003).

| | | |
|---|---|---|
| South Asia | 0.021 | 6.1 |
| World | 0.027 | 1.2 |

The data from the IIASA database were also used in the report World Agriculture: Towards 2010 (Alexandratos 1994), the predecessor of the WATO 2015/30 report. These data are derived from the correlation between population density and non-agricultural land use per person based on China (the only country for which systematic data were available for 2000 counties).The higher the density, the lower the area per capita. This correlation between population density is also identified by other authors (#ref in build-up land paper USA) . Consequently, the lowest build-up land per capita is in Western Europe, Japan and South Asia (respectively 0.026, 0.020 and 0.021 ha/cap). The area build-up land per capita in the developing countries with low population densities is higher that most of the industrialised countries in contrary what one would expect based on the level of industrialisation and per capita income. The area build-up land in East Europe/C.I.S. & Baltic States, Caribbean & Latin America and sub-Saharan Africa is respectively 0.034, 0.034, 0.040 hectare per capita. Globally, the build-up area is 1.2%, compared to slightly more than 2% reported by UNEP (UNEP 2002b). This share is expected to increase to some 3 to 4% in 2030.

Despite the relatively small build-up area compared to the total land (between 0.1 and 3,4% excluding Japan and South Asia), the impact on agricultural land use is much larger. In the land scarce region of South Asia some 45% of the land area with crop potential is occupied by housing and infrastructure (FAO 2000a). In general, a significant portion of the build-up land is likely to be at the expense of high-quality agricultural land, because historically the major urban cities are situated in river valleys and along coastal regions with good quality land. Different authors indicate that most of the agricultural land lost in competition with urban expansion comes from high quality agricultural land (various sources in (Döös and Shaw 1999). Kendall and Pimental (1994) indicate a loss of 2-4 million ha, (Nors *et al*. 1992 in (Döös and Shaw 1999)) 5 million ha and Döös *et al.* 2.1 million ha (Döös and Shaw 1999). On the other hand, Scherr (Scherr 1999) reports that some 20 to 60% of the land in some metropolitan areas is still available for crop production. Other studies indicate that productivity in or near urban areas increases with urban expansion. If a loss of 100 million ha is assumed based on a loss of 0.04 hectare per 1000 inhabitants the total of cropland in 2030 is 100 million hectares of which 60 million with crop production potential (FAO 2003b). This is only a fraction of the total land balance. Assuming a total loss of 5 million ha per year, this is only 0.1% of the total agricultural cropland presently in use and is equal to a limited 0.4% of the total global area very suitable for crop production. In regions with high population densities such as India and China that have limited potential to increase the area under crop production, land use competition can be limiting factor (FAO 2003b).

## APPENDIX L

### HARVEST INDEXES

The harvest index refers to the production of residues before these commodities are included in the FAO statistics. By-products (secondary residues) become available in later stages of the food chain.

*Table 11.* Harvest indexes, based on dry weight. Source: (FAO 2000b).

| | high input system | low input system | medium put system | | high input system | low input system | medium put system |
|---|---|---|---|---|---|---|---|
| wheat | 0.43 | 0.23 | 0.33 | sugar beet | 1.00 | 1.00 | 1.00 |
| rice | 0.43 | 0.30 | 0.36 | sugar & sweeteners | 1.00 | 1.00 | 1.00 |
| barley | 0.40 | 0.20 | 0.30 | pulses | 0.30 | 0.15 | 0.23 |
| maize | 0.40 | 0.20 | 0.30 | treenuts | 0.30 | 0.25 | 0.28 |
| rye | 0.35 | 0.18 | 0.26 | soybeans | 0.30 | 0.15 | 0.23 |
| oats | 0.40 | 0.20 | 0.30 | groundnut | 0.30 | 0.25 | 0.28 |
| millet | 0.30 | 0.15 | 0.23 | sunflowers | 1.00 | 1.00 | 1.00 |
| sorghum | 0.30 | 0.14 | 0.22 | rapeseed | 0.25 | 0.15 | 0.20 |
| cereals, other | 0.40 | 0.20 | 0.30 | cottonseed | 0.07 | 0.05 | 0.06 |
| cassava | 0.50 | 0.30 | 0.40 | palm kernels | 0.25 | 0.15 | 0.20 |
| potatoes | 0.60 | 0.30 | 0.45 | vegetables | 0.71 | 0.71 | 0.71 |
| sweet potatoes | 0.55 | 0.30 | 0.43 | fruit (excl. wine) | 0.33 | 0.33 | 0.33 |
| yams & other roots | 0.60 | 0.30 | 0.45 | stimulants | 0.30 | 0.15 | 0.23 |
| sugar cane | 0.78 | 0.78 | 0.78 | spices | 0.25 | 0.15 | 0.20 |

### PROCESSING RESIDUE COEFFICIENTS

*Table 12.* Processing residue coefficients. Av. c.e. = average conversion efficiency. Data indicate the usable percentage of the processed quantity in dry weight. Source: (FAO 2000d).

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| conversion | wheat to flour | whole potato tuber to skinned tuber | whole sweet potatoes tuber to skinned tuber | whole tuber to skinned tuber (yams and other roots and tubers) | sugarcane stems to raw centrifugal cane sugar | sugar beet tubers to raw centrifugal beet sugar | sugar & sweeteners | pulses |
| residue | bran and germ | bran and hulls | bran and hulls | bran and germ | bran | oats offal | bran | bran |
| av. c.e. | 79 | 67 | 72 | 82 | 80 | 53 | 86 | 90 |
| conversion | tree nuts | soybeans | groundnut shelled to unshelled | sunflower seed to oil | rapeseed to oil | sugarcane stems to raw centrifugal cane sugar | sugar beet tubers to raw centrifugal beet sugar | sugar & sweeteners |
| residue | bran, hulls, pots, germ | skin | skin | skin | skin | molasses and bagasse | molasses | |
| av. c.e. | 85 | 60 | 70 | 70 | 70 | 75 | 75 | 100 |
| conversion | pulses | tree nuts | soybeans | groundnut shelled to unshelled | sunflower seed to oil | rapeseed to oil | cotton | |
| residue | | | cakes | | cakes | cakes | | |
| av. c.e. | 100 | 27 | 79 | 13 | 41 | 38 | 93 | 50 |
| conversion | other oilcrops | soybean oil | groundnut oil | sunflower oil | other vegetable oils | vegetables | fruit (excl. wine) | |
| residue | | | | | | | | |
| av. c.e. | 55 | 90 | 90 | 100 | 90 | 80 | 80 | |

## WASTE RATIOS

Wastes are included in the FAO Food Balance Sheets statistics and include post-harvest losses, but exclude kitchen losses; 'from farm truck to kitchen door'.

*Table 13.* Waste ratios (average of 1997, 1998 and 1999; percentage of supply). Source: (FAO 2000d).

| | cereals | roots and tubers | sugar-crops | pulses | oilcrops | vegetables and fruit |
|---|---|---|---|---|---|---|
| North America | 0.3 | 10.4 | 0.0 | 2.2 | 6.1 | 4.8 |
| Oceania | 3.2 | 1.9 | 0.0 | 3.7 | 0.4 | 3.7 |
| Japan | 0.8 | 4.3 | 0.0 | 4.5 | 1.8 | 9.7 |
| Western Europe | 1.8 | 4.8 | 0.3 | 1.9 | 0.9 | 8.3 |
| East Europe | 4.9 | 11.8 | 0.0 | 4.8 | 3.2 | 7.7 |
| C.I.S. and Baltic States | 2.2 | 2.9 | 0.5 | 5.6 | 2.6 | 3.5 |
| sub-Saharan Africa | 9.3 | 17.4 | 4.6 | 3.3 | 1.5 | 9.6 |
| Caribbean & Latin America | 7.9 | 10.9 | 0.7 | 3.9 | 1.2 | 16.1 |
| Near East & North Africa | 7.9 | 9.6 | 0.2 | 4.3 | 2.9 | 11.5 |
| East Asia | 4.8 | 6.1 | 2.1 | 4.3 | 3.4 | 8.3 |
| South Asia | 2.9 | 13.2 | 0.1 | 3.1 | 3.0 | 8.9 |
| World | 4.0 | 9.4 | 0.7 | 3.4 | 2.9 | 9.0 |

## APPENDIX M

## THE DEMAND AND SUPPLY OF WOOD IN 2050

*Table 13.* Theoretical demand and supply scenarios (IRW = industrial roundwood, FW = fuelwood, (un)comm. sp. (un)av. = (un)commercial species (un)available; million $m^3$).

| | | 1998 | 2050 low | 2050 medium | 2050 high | 1998 | 2050 low | 2050 medium | 2050 high | 1998 | 2050 low | 2050 medium | 2050 high |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | sub-Saharan Africa | | | | Caribbean & Latin America | | | | Near East & North Africa | | | |
| Demand | IRW | 60 | 63 | 83 | 104 | 130 | 109 | 144 | 178 | 23 | 28 | 37 | 46 |
| | FW from forest supplies | 147 | 161 | 209 | 258 | 91 | 98 | 128 | 157 | 9 | 9 | 12 | 15 |
| | FW from non-forest supplies | 298 | 327 | 425 | 523 | 185 | 199 | 261 | 322 | 17 | 19 | 25 | 31 |
| Supply | Industrial plantations | | 21 | 37 | 87 | | 40 | 121 | 198 | | 2 | 12 | 19 |
| | Non-industrial plantations | | 7 | 12 | 28 | | 22 | 49 | 81 | | 3 | 7 | 11 |
| | Closed forest, comm. sp., av. | | 95 | 95 | 95 | | 162 | 162 | 162 | | 11 | 11 | 11 |
| | Closed forest, uncomm. sp., av. | | 170 | 170 | 170 | | 292 | 292 | 292 | | 0 | 0 | 0 |
| | Closed forest, comm. sp. unav. | | 120 | 120 | 120 | | 653 | 653 | 653 | | 13 | 13 | 13 |
| | Closed forest, uncomm. sp., unav. | | 215 | 215 | 215 | | 1,250 | 1,250 | 1,250 | | 0 | 0 | 0 |
| | Total annual growth in forests | | 628 | 649 | 715 | | 2,419 | 2,526 | 2,636 | | 30 | 44 | 55 |
| | Surplus (+) or shortage (-) medium demand scenario | | 754 | 774 | 841 | | 2,403 | 2,510 | 2,620 | | 5 | 19 | 30 |
| | | North America | | | | Oceania | | | | Japan | | | |
| Demand | IRW | 629 | 754 | 992 | 1,230 | 24 | 45 | 59 | 73 | 75 | 106 | 140 | 173 |
| | FW from forest supplies | 58 | 11 | 14 | 17 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | FW from non-forest supplies | 19 | 4 | 5 | 6 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Supply | Industrial plantations | | 122 | 242 | 349 | | 37 | 70 | 96 | | 26 | 54 | 40 |
| | Non-industrial plantations | | 0 | 0 | 0 | | 0 | 0 | 0 | | 0 | 0 | 0 |
| | Closed forest, comm. sp., av. | | 799 | 799 | 799 | | 97 | 97 | 97 | | 10 | 10 | 10 |
| | Closed forest, uncomm. sp., av. | | 0 | 0 | 0 | | 19 | 19 | 19 | | 2 | 2 | 2 |
| | Closed forest, comm. sp. unav. | | 628 | 628 | 628 | | 185 | 185 | 185 | | 11 | 11 | 11 |
| | Closed forest, uncomm. sp., unav. | | 0 | 0 | 0 | | 36 | 36 | 36 | | 2 | 2 | 2 |
| | Total annual growth in forests | | 1,549 | 1,668 | 1,776 | | 373 | 407 | 433 | | 52 | 79 | 65 |
| | Surplus (+) or shortage (-) medium demand scenario | | 571 | 691 | 798 | | 315 | 348 | 374 | | -88 | -60 | -74 |
| | | C.I.S. & Baltic States | | | | West Europe | | | | East Europe | | | |
| Demand | IRW | 146 | 141 | 185 | 229 | 266 | 286 | 376 | 467 | 55 | 51 | 67 | 83 |
| | FW from forest supplies | 39 | 10 | 13 | 16 | 25 | 5 | 6 | 8 | 8 | 1 | 2 | 2 |
| | FW from non-forest supplies | 13 | 3 | 5 | 6 | 8 | 2 | 2 | 3 | 3 | 0 | 1 | 1 |
| Supply | Industrial plantations | | 17 | 52 | 41 | | 48 | 85 | 113 | | 3 | 11 | 13 |
| | Non-industrial plantations | | 0 | 0 | 0 | | 0 | 0 | 0 | | 0 | 0 | 0 |
| | Closed forest, comm. sp., av. | | 973 | 973 | 973 | | 419 | 419 | 419 | | 122 | 122 | 122 |
| | Closed forest, uncomm. sp., av. | | 2 | 2 | 2 | | 47 | 47 | 47 | | 13 | 13 | 13 |
| | Closed forest, comm. sp. unav. | | 305 | 305 | 305 | | 75 | 75 | 75 | | 20 | 20 | 20 |
| | Closed forest, uncomm. sp., unav. | | 1 | 1 | 1 | | 8 | 8 | 8 | | 2 | 2 | 2 |
| | Total annual growth in forests | | 1,297 | 1,332 | 1,321 | | 596 | 634 | 662 | | 159 | 168 | 170 |
| | Surplus (+) or shortage (-) medium demand scenario | | 1,125 | 1,160 | 1,150 | | 226 | 264 | 291 | | 94 | 103 | 105 |
| | | East Asia | | | | South Asia | | | | World | | | |
| Demand | IRW | 219 | 273 | 360 | 446 | 45 | 44 | 58 | 72 | 1,672 | 1,900 | 2,500 | 3,100 |
| | FW from forest supplies | 173 | 192 | 250 | 307 | 119 | 121 | 158 | 194 | 671 | 609 | 792 | 975 |
| | FW from non-forest supplies | 351 | 390 | 510 | 630 | 242 | 246 | 322 | 398 | 1,136 | 1,191 | 1,558 | 1,925 |
| Supply | Industrial plantations | | 50 | 220 | 472 | | 4 | 32 | 59 | | 370 | 935 | 1,487 |
| | Non-industrial plantations | | 24 | 60 | 127 | | 48 | 135 | 248 | | 103 | 262 | 496 |
| | Closed forest, comm. sp., av. | | 247 | 247 | 247 | | 10 | 10 | 10 | | 2,945 | 2,945 | 2,945 |
| | Closed forest, uncomm. sp., av. | | 41 | 41 | 41 | | 5 | 5 | 5 | | 590 | 590 | 590 |
| | Closed forest, comm. sp. unav. | | 166 | 166 | 166 | | 12 | 12 | 12 | | 2,189 | 2,189 | 2,189 |
| | Closed forest, uncomm. sp., unav. | | 33 | 33 | 33 | | 7 | 7 | 7 | | 1,554 | 1,554 | 1,554 |
| | Total annual growth in forests | | 560 | 767 | 1,086 | | 87 | 202 | 342 | | 7,750 | 8,475 | 9,260 |
| | Surplus (+) or shortage (-) medium demand scenario | | 450 | 657 | 976 | | 186 | 301 | 442 | | 6,042 | 6,767 | 7,553 |

## APPENDIX N

## THE DEMAND FOR BIOMASS IN 1998 AND 2050

*Table 14.* Biomass turnover in the food production system ($EJy^{-1}$).

| Region 1998 | food & processing | feed | grasses & fodder | harvest residues | residues used for feed | scavenging biomass | GRAND TOTAL |
|---|---|---|---|---|---|---|---|
| West Africa | 1 | 0 | 2 | 2 | 0 | 0 | 6 |
| Central-Africa | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| East-Africa | 1 | 0 | 4 | 1 | 0 | 0 | 6 |
| Southern-Africa | 1 | 0 | 2 | 1 | 0 | 0 | 4 |
| Central America | 1 | 0 | 2 | 1 | 1 | 0 | 5 |
| Caribbean | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| South-America | 4 | 1 | 12 | 7 | 3 | 1 | 24 |
| North Africa | 1 | 0 | 1 | 1 | 0 | 0 | 3 |
| Near East | 2 | 1 | 2 | 2 | 1 | 0 | 7 |
| South-East Asia | 3 | 0 | 1 | 4 | 1 | 0 | 10 |
| East Asia | 9 | 3 | 5 | 16 | 6 | 3 | 36 |
| Northern South Asia | 2 | 0 | 1 | 3 | 1 | 1 | 7 |
| Southern South Asia | 6 | 0 | 3 | 9 | 2 | 3 | 20 |
| North America | 3 | 3 | 5 | 15 | 2 | 0 | 26 |
| Oceania | 0 | 0 | 4 | 1 | 1 | 0 | 6 |
| Japan | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| Western Europe | 3 | 2 | 4 | 7 | 3 | 0 | 16 |
| East Europe | 1 | 1 | 1 | 3 | 0 | 0 | 5 |
| C.I.S. and Baltic States | 1 | 1 | 3 | 4 | 1 | 0 | 9 |
| sub-Saharan Africa | 3 | 0 | 9 | 5 | 1 | 1 | 17 |
| Caribbean & Latin America | 6 | 1 | 14 | 8 | 4 | 1 | 30 |
| Near East & North Africa | 2 | 1 | 3 | 3 | 1 | 0 | 9 |
| East Asia | 13 | 3 | 6 | 21 | 7 | 3 | 45 |
| South Asia | 8 | 0 | 4 | 11 | 2 | 4 | 27 |
| World | 41 | 13 | 51 | 78 | 22 | 9 | 192 |

| Region 2050 | food & processing | feed | grasses & fodder | harvest residues | residues used for feed | scavenging biomass | GRAND TOTAL |
|---|---|---|---|---|---|---|---|
| West Africa | 4 | 0 | 11 | 8 | 1 | 1 | 24 |
| Central-Africa | 1 | 0 | 2 | 2 | 0 | 0 | 6 |
| East-Africa | 3 | 0 | 20 | 5 | 1 | 2 | 30 |
| Southern-Africa | 2 | 0 | 8 | 2 | 0 | 1 | 12 |
| Central America | 2 | 1 | 5 | 3 | 1 | 0 | 11 |
| Caribbean | 0 | 0 | 1 | 0 | 0 | 0 | 2 |
| South-America | 7 | 1 | 23 | 11 | 5 | 2 | 45 |
| North Africa | 2 | 0 | 1 | 2 | 1 | 0 | 6 |
| Near East | 4 | 2 | 7 | 8 | 2 | 1 | 21 |
| South-East Asia | 6 | 1 | 4 | 7 | 2 | 1 | 19 |
| East Asia | 12 | 8 | 8 | 31 | 7 | 5 | 64 |
| Northern South Asia | 4 | 0 | 5 | 8 | 2 | 7 | 24 |
| Southern South Asia | 12 | 0 | 8 | 17 | 4 | 15 | 52 |
| North America | 5 | 4 | 5 | 19 | 2 | 0 | 33 |
| Oceania | 0 | 0 | 4 | 1 | 1 | 0 | 6 |
| Japan | 1 | 0 | 0 | 1 | 0 | 0 | 2 |
| Western Europe | 3 | 2 | 3 | 6 | 3 | 0 | 14 |
| East Europe | 1 | 1 | 1 | 3 | 0 | 0 | 6 |
| C.I.S. and Baltic States | 1 | 1 | 3 | 5 | 1 | 0 | 10 |
| sub-Saharan Africa | 9 | 0 | 41 | 17 | 2 | 4 | 71 |
| Caribbean & Latin America | 10 | 2 | 28 | 15 | 6 | 2 | 57 |
| Near East & North Africa | 5 | 2 | 9 | 10 | 3 | 2 | 28 |
| East Asia | 18 | 9 | 12 | 38 | 9 | 6 | 83 |
| South Asia | 16 | 0 | 13 | 25 | 7 | 22 | 77 |
| World | 69 | 23 | 119 | 140 | 34 | 37 | 388 |

Scenario details: medium population and consumption growth, high harvest index, 2050 feed composition, feed conversion efficiency and production system.

Note that residues for feed and scavenging are not included in the total to avoid double counting. In total some 10 Pg dry weight phytomass is being produced globally on behalf of the food production system in 1998, equal to 192 EJ. Compared to the annual human food intake of 0.04 EJ leads to an overall efficiency of less than one promille.

Half of the biomass globally produced can be allocated to the animal production system, while less than one fifth of the food intake measured in kcal comes from animal products. In total 5 Pg is allocated to the animal production system, the IMAGE model indicates 4,9 Pg (IMAGE-team 2001). Of the remaining 50% not allocated to animal feed, is the largest part largest part harvesting and processing residues and waste and seed.

The largest biomass categories are the production of harvesting residues and the animal intake of grass, fodder and biomass from scavenging and are also the least certain. The production of harvesting residues is dependant on the species used. Modern, hybrid rice species have HI's (the part of a plant usable) of 0.50-0.55 while traditional varieties have a HI of 0.2. The calculations are based on HI's typical for high input systems common in the industrialised countries. Note that some of the large biomass categories are considerable uncertain (grass, fodder and scavenging biomass) because of a lack of data on actual biomass pasture biomass turnover in the animal production system. Increases in production have been partially the result of increasing grazing intensity. A clear view on the production potential of these pastures and related supply demand interactions is not present, as the overestimated problem of overgrazing clearly shows (FAO 2003b).

To the year 2050 the total demand for biomass is expected to double to 20 Pg, the total consumption of food (in kcal) increases in the same period with 79%. The calculated biomass consumption is very much dependant on the values for feed conversion efficiency, harvest index and obviously population growth and increase in meat consumption.

## APPENDIX O

### PAST GLOBAL FOOD PROJECTIONS AND PROJECTIONS ERRORS

During the last decades many studies were carried out on the future of global food security. The results range from very negative (large famines) to very positive (a carrying capacity of 157 billion). In 1999 two researchers, Bo Döös and Roderick Shaw published a sensitivity analysis in which the impact of various aspects on the global food demand and supply to 2025 is discussed (Döös and Shaw 1999). In 2001 the IFPRI published a discussion paper in which the accuracy of these global food projections is estimated. Based on these two studies, supplemented by other reports and our own analysis, some conclusions are drawn on the future of global food security (IFPRI 2001b). In this section the focus on projections from the IFPRI, USDA and FAO, because:

- these projections are generally considered as the most detailed and reliable projections available and
- all three organizations project for the coming decades a situation without severe global food security problems, although much more pessimistic views are also possible (see next section).

Projections on food production and consumption were found to vary much more than population projections. The uncertainties and reliability of population projections is discussed in Appendix E. At the regional level food consumption and production forecast errors in the range of +/-10 to 40% are common, with exception to 90% and higher. Also here, global aggregated data show much smaller projection errors. Both FAO and USDA projections seem to have systematically underestimated both production and consumption, globally between –13 to –37% (projection of 1967/1975). The USDA projection errors of projections between 1960 to 1970 were between –4.1 to –14%. The projection errors are especially large for the developing countries, although projection errors for the EU and USA were also usually two digit number indicating the overwhelming effect of domestic policies which is usually too complex to be modelled accurately. Note that not all errors necessarily indicate flaws in the used models, but also reflect errors in the used exogenous projections such as exchange rates, GDP, population or sudden large changes in policy.

The IFPRI and Döös conclude state that:

1. Many or most of the factors that influence food supply have very limited predictability and the functioning of the entire socio-economic system is poorly understood. Examples 1.) One of the most dramatic changes that shows the impact of the latter is the dramatic drop in production and consumption after the collapse of communism in East Europe and the C.I.S. and the Baltic States (see section 3.1.2). In general, all models and projects do not include dramatic changes such as war, rapid policy shifts or climate change. 2.) The correlation between two very of not most important demand side parameters GDP and population growth is subject of debate now for many decades (see also issue 4).
2. Data on the global food production system are often lacking or inaccurate (IFPRI 2001b) (Döös and Shaw 1999; White 2000).

These factors may be considered as the most important ones, factors 3, 4 and 5 mentioned in the following section are also relevant.

### RESOURCE CONSTRAINTS AND GLOBAL FOOD SECURITY

The projection by the IFPRI, USDA and FAO have in common that they are quite positive on the *global* food security situation meaning that supply is projected to increase as the same rate as demand. All three studies predict:

- the area cropland under cultivation is going to increase, although most production growth will come from increasing yields.
- world food prices will remain stable or decrease slightly, although at a slower rate than in the past.
- the developing countries will become increasingly dependant on imports, but these demands can be met by the developed countries.
- food insecurity problems are likely to continue for the coming decades, notably sub-Saharan Africa and South Asia.

There are however many other reports that indicate more severe problems about the long-term capability of the earth to sustain increasing population and consumption. Already in 1798 Malthus pointed out in his famous '*Essay on the Principle of Population Growth*' the dangers of ever growing population and consequently increasing demand for natural resources. A review of publications of the earth carrying capacity shows that estimates range from 1 billion to 157 billion (Cohen 1995). The Club of Rome's report 'Limits to growth' (Meadows, 1972) is another example received world wide attention, but many more studies have been published since. The most recent pessimistic studies are '*Full House: Reassessing the Earth' Population Carrying Capacity'* (Brown and Kane 1994) and a follow up '*Who Will Feed China? Wake-up call for a Small Planet'* (Brown 1995)[36].

Since there is little disagreement on the increasing demand for food, feed, wood and other ecological services, the difference between the pessimistic and optimistic studies relates to the capacity of the earth to provide these services. Well known supply side issues are the overuse and scarcity of water, soil degradation (Stalinisation, soil depletion, desertification, loss of topsoil), deforestation and the wood fuel crisis and ecosystem pollution by agricultural chemicals. Döös and IFPRI identify several factors why these pessimistic projections have not become reality (yet). Note that factors 1 and 2 that are mentioned in the previous paragraph are also relevant.

3. Many estimates are based on very subjective and quantitative assessments of the factors that influence food production; in many cases positively or negatively influencing factors have been deliberately exaggerated to address a certain issue to the policy makers (Döös and Shaw 1999).
4. Most researchers are free to focus on a subset of variables that particularly concern them such as stagnating yields, water constraints etc. Focusing on these issues separately and then adding them up easily results in large problems. In reality, these factors are part of a much larges and complex system and few models include take into account all major influencing factors, substitution options and feedback loops (IFPRI 2001b). Döös (1999) concludes that 'the knowledge of (..) socio-economic factors that have an influence on food demand and production is very limited. This lack of knowledge is even more pronounced with regard to the many *interactive* processes that take place (…). And even if very reliable elasticities were available, even the most sophisticated economic models cannot predict economic development for more than a few years into the future'.

[36] By the end of the 90's a series of papers have been published in which the historic low stock levels, increasing world cereal prices and stagnating yield increases are seen as indicators of upcoming global food shortages. These trends were however the result of a combination of bad harvests in the US in 1993 and 1995, policy changes and other factors. By the end of the 90's cereal production hit record levels and prices were all time low (IFPRI 2001a).

Some more optimistic scenarios and views on the earth' capacity to produce food and wood were also held by various author's (although these reports did not receive as much attention). Critics on these reports is that (but see also remarks 1 to 4):

5. There are difficulties in distinguishing between what is theoretically possible and what can be achieved realistically (Döös and Shaw 1999).

As said, the difference between the pessimistic and optimistic studies lies in the rather subjective analysis of the status and capacity of the resource base of production. The more pessimistic studies hold the view that given these uncertainties, caution is needed (the 'better safe than sorry principle'). Secondly, there are concerns of the potential of technology to alleviate pressure on the natural resources or to increase productivity, both concerning the technical potential and concerning the possible negative environmental effects of further intensification. The first issue is further debated in Appendix Q. Unfortunately, most of the biological and physiological processes that determine the earth carrying and regeneration capacity are poorly understood, although it likely that science eventually will be capable of reducing many of these uncertainties related to e.g. soil erosion. Up till then, much depends on more qualitative analysis and expert judgement on the status and carrying capacity of the earth' resources.

Note that even if detailed scientific information and insights on the biological and physiological processes are available, this information is not likely to be of much help in discussions on the sustainability. There is already a general agreement that most forms of environmental degradation and overuse are caused by improper use of resources or can at least partially be avoided by increasing the efficiency. Consequently, it is more the entire socio-economic system that determines the level of environmental degradation, rather than the demand itself.

As said earlier in this study, the functioning of the entire socio-economic system is poorly understood. By looking at the various forms of environmental degradation however, one can only conclude that under the current market conditions, environmental degradation is often not included in prices (this goes especially long-term effects). At this moment, bioenergy production certification schemes are under development to ensure environmentally sound production systems. Such certification systems are primarily designed to avoid or minimize the direct impact on the environment. So called leakage effects (second or higher order effects) are usually left out. Although the functioning of the entire socio-economic system is poorly understood, both regional and global markets in general are quite dynamic and responsive. Consequently, the exact cause and effect of market interference by bioenergy production systems and trade are difficult to pinpoint.

Note that some of the issues dealt with in this section seem to have been overestimated, at least according to some:

- Desertification.
    - 'Desertification is a serious form of dryland degradation. In the 1970's and 80's it was argued that the Sahara was spreading rapidly southwards as part of an irreversible expansion of the world's deserts. Since then, counter-arguments have been growing in force backed up by strong empirical evidence from remote sensing activities (Nicholson and Tucker, 1998; Prince *et al*. 1998 in (FAO 2000a). That is, the desert margins are quite dynamic because of natural climate variation and the issue is more one of localised dryland degradation because of overgrazing, excessive fuel collection, bad tillage practices and inappropriate cropping systems. Nonetheless, there has been some expansion of the deserts and dryland degradation although quantification is not precise (Dregne and Chou, 1992 in (FAO 2000a)).'

    - '…. recent thinking points to a growing consensus that the past estimates of areas affected were greatly exaggerated' (Alexandratos 1994) in (Döös and Shaw 1999).
- The global wood fuel crisis. The belief that the developing countries were facing a major "woodfuel crisis" emerged in the mid-1970s.
    - 'At the global level, forecasts of scarcity have probably been exaggerated. "Doom scenarios" under which wood-dependent countries would lose all their forests to firewood collection have not transpired (…). The error was caused by the mistaken assumption that forests were the sole source of firewood (RWEDP, 1997 in Matthews, 2000).' (Matthews 2000).
    - 'It has been almost thirty years since Eric Eckholm caused global alarm with his highly publicized book, '*The Other Energy Crisis: Fuelwood'*. Eckholm predicted a looming fuelwood shortage as rising numbers of poor people over-exploited forests to meet their energy needs. That would make life harder for millions of women and children who would have to walk long distances to gather fuelwood. Such claims spurred donors and policymakers into action and scores of fuelwood projects quickly followed. These projects encouraged families to plant trees, use more efficient stoves, and substitute fuelwood with other sources of energy. Pretty soon, however, people realized that claims of an impending fuelwood crisis were exaggerated and most fuelwood projects were failing. Contrary to prediction, fuelwood prices generally failed to rise and farmers showed little interest in planting trees to produce such a low value product. Policymakers soon concluded there was no fuelwood crisis and interest in the issue declined precipitously.'
- Land degradation
    - 'The critical issues are whether the area suffering from degradation will expand in the future, and whether the projected intensification of production will cause degradation to deteriorate further and undermine food security. According to some analysts the seriousness of the situation has been overestimated (Crosson 1997 in (FAO 2000a); (Scherr 1999). For others, however, land degradation is a major threat to food security and has been so bad that it has negated many of the productivity improvements of the past' (Pimentel *et al*. 1995 and UNEP 1999 in (FAO 2000a).
    - 'some studies are (…) arguing that degradation estimates are overstated. A major reason suggested for the overestimation of land degradation has been underestimation of the abilities of local farmers (Mazzucato and Niemeijer 2001). These authors argue that ' … experts need to discriminate more carefully between a naturally bad state, a temporary bad state and a degraded state of land'. (UNEP 2002b).
    - 'There is still great uncertainty as to the extent and severity of land degradation and desertification, but there are indications that in many cases past assessments were overestimates. In addition, the impact of land degradation on productivity seems to be less severe than sometimes suggested.' (FAO 2003b)
- Deforestation
    - 'Probably the greatest conceptual shift has been the development, throughout the 1990's, of a clear consensus that there is no impending "global forest crisis". In part, this recognizes that previous projections of consumpti0on of wood products have not adequately taken into account all relevant factors ' (FAO 2003b)

## IMPLICATION FOR DISCUSSIONS ON BIOENERGY PRODUCTION AND TRADE

Regardless of the scientific validity, knowledge and uncertainties, most of the environmental mentioned in the latter section have received much attention from both NGO's, the international scientific community, policy makers and are well known by the public. Although the *total global* *impact* of some environmental issues was overestimated according to some authors, anyone will agree that regional problems are likely to persist or aggravate. In combination with the continued scientific uncertainties that only partially can be solved (almost by definition since this relates to predictions), debates on the causes, effects and severity of environmental degradation are likely to continue for many years, the same goes for leakage effects.

For the acceptance of bioenergy, much if not all will depend on the expert opinion from the most important stakeholders. Considering a situation where bioenergy from imported biomass is being produced at higher prices than conventional fuels, any emergence of an alleged unsustainable issue related to bioenergy production or trade is likely to be a major threat to the acceptance especially by the public. Most of the discussions are likely too complicated and science can only partially provide answers, especially because any projection is inherently uncertain.

Organisation such as the World Resources Institute, World Watch Institute, World Wildlife Fund, Greenpeace have a long history of analysis of environmental issues *and* public relations. These organisations also represent (at least partially) the environmental minded consumers that are buying the bioenergy. These discussions are especially important because, contrary to ecological services such as food production and partially wood production, there are substitutes for $CO_2$ emission reductions. Unfortunately, we did not find official statements, only the World Resources Institute states: 'Because biofuel production would likely compete with conventional agricultural land uses for food production, the strategy appears best suited to land- and food-surplus countries or regions or on lands unsuitable for sustainable annual crop production.'

We hope that by giving this brief overview, we give the reader some insight in discussion that are going on or can be expected when debating the sustainability of large scale bioenergy production and trade..

## DATASETS AND UNCERTAINTIES

Generally, high quality data are available for trade goods such as cereals, fish, meat or timber products and some basic productivity factors such as fertilizer application and yields. Data on products that are exchanged on informal markets or consumed directly such as fuelwood, subsistence foodstuff and forest food are patchy and often modelled (White 2000). Data on the biological capacity that support production such as the size of fish stocks, biomass densities, soil formation, water purification and recycling are often very uncertain (White 2000).

The most widely used dataset, and only global dataset available, is the FAO AGROSTAT database (FAO 2002a). The FAO database contains detailed data on production, import, export, stock change, seed use, wastes for all agricultural commodities as well as data on the production of wood and wood products, land use and prices to name the most important ones. Data are available for 1961 to present (for most of the parameters covered) and per country. Despite the level of detail and amount of data, the data bases related to various components of the global food production system are insufficient and often inaccurate to model food demand and supply (as also becomes clear in various section of world growth). Especially data for the developing are notoriously unreliable and based on estimates rather than hard data. Note that this does not indicate that the FAO does not do their job properly, it is only an indicator of the many uncertainties related to such global datasets.

## APPENDIX P

## GDP PROJECTIONS, COMPARISON OF WORLD BANK AND IMAGE/SRES SCENARIOS

The second most important driver for increasing consumption of food and energy is income. Despite this relative importance, 'the current state of modelling long-term economic growth is not well developed, not least because the dominant factors of long-run productivity growth, such as the role of institutions and technological change remain exogenous to models' (IPCC 1996). This is reflected in the large variation of per capita GDP projections. This effect is amplified due to fact that small differences in growth rate, add up to huge differences in GDP per capita when computed over a 50 year period, in the order of magnitude of a factor 10 for regional average per capita GDP data (IPCC 1996).

No attempts were made to calculate GDP scenarios and corresponding changes in food consumption or energy use for various methodological problems. Instead, results for existing studies. For future trends in consumption of agricultural products, the study 'Agriculture Towards 2015/2030' (FAO 2000a) may be considered as the most reliable and up to date study presently available. Data are supplemented by IMAGE data (IMAGE-team 2001). The FAO study uses the latest GDP projections from the World Bank (WB 2001) in combination with expert judgement. The scenarios for energy consumption are based on studies from the International Energy Agency (WEO 2002). Data obtained from the World bank are compared to IPCC SRES scenarios to get an idea of the cumulative effect of such developments, which in the case of the SRES scenarios are combined into different comprehensive scenarios. Per capita GDP figures are shown in figure 8.

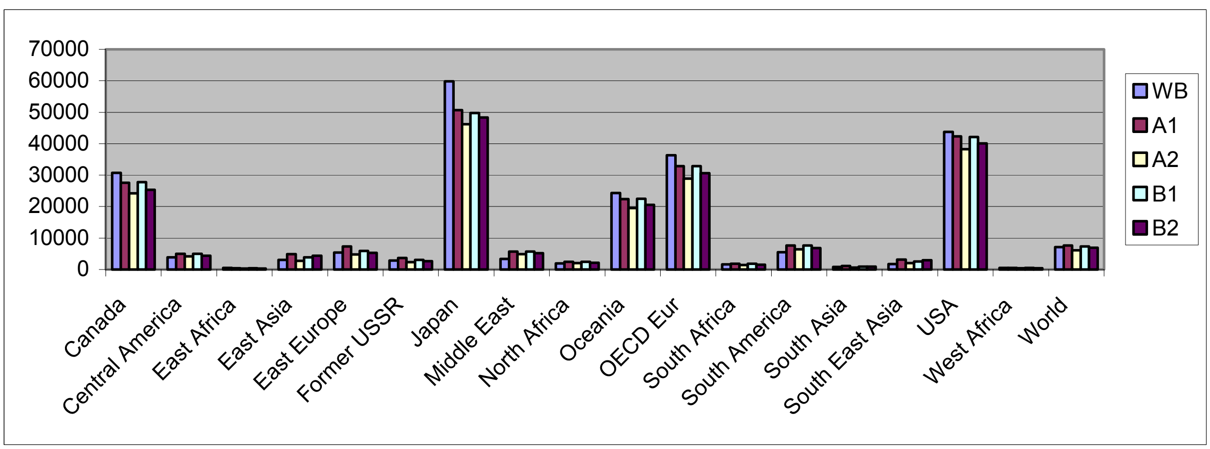


*Figure 8.* GDP per capita in 2050. WB = Worldbank projections, A1, A2, B1 and B2 are the different IPCC scenarios (IMAGE-team 2001).

Two remarkable differences between the Worldbank projections and the SRES scenarios are clearly visible. The Worldbank projections are higher than the SRES scenarios for the developed world and lower for the majority of the developing countries. The difference in the global average total increase in consumption is much less. This corresponds with recent criticism on SRES GDP scenarios. Complaints are that the initial GDP gaps are overstated in the beginning and being closed by the end of this century (Castles and Henderson, 20..) as a result of build in convergence of GDP. Since the SRES scenarios are based on possible future scenarios and are internationally accepted and widely used, it is concluded that a world with more converging GDP developments in the next decades is possible. The observed difference in GDP projections could very well be also an explanation for the relative high consumption of animal products compared to our/FAO calculations.

## APPENDIX Q

## SOIL EROSION

Together with fresh water shortages, soil erosion is identified as *'a major threat to global agriculture and has negated many of the gains in land productivity of recent decades'* , at leas according to some (e.g. Pimental *et al*. 1995 and UNEP 1999 in (FAO 2003b)).

In 1987 UNEP requested an global assessment on soil degradation to help policy makers better understand the dangers of inappropriate land and soil management. The result was the GLASOD dataset, later followed by a more detailed dataset for South and South East Asia. The GLASOD dataset has been criticised frequently for being crude, inaccurate and based on (subjective) expert judgement rather than measurements (White 2000), resulting in a continuous debate.

The reported rate of soil erosion is 10 to 20 times the floor renewal rate in the temperate regions and 20 to 40 times in the tropics. The total annual global loss of cropland has been estimated to be between 5 and 12 million ha $yr^{-1}$, the cumulative production loss in 2030 in estimated at 17% and Oldeman (1998) estimates a cumulative loss of global cropland productivity between 1945 and 1990 of about 13%. Crosson (1997) suggest that the average loss of cropland productivity since the mid 50's was lower than 0.3% annually. Norse (1992) points out that soil erosion is caused by deforestation that accounts for 43% of the total erosion, overgrazing (29%) and mismanagement (24%).

Due to a lack of data on the current extend of degradation, ecosystem dynamics and maximum grazing intensities does not allow a more detailed analysis within the limitations of this study. We considered it beyond the scope of this study to go into further detail in the (extensive) debates about soil erosion, although we tend to follow the view of the FAO that soil erosion is not likely a major threat the agriculture, although some 'hot spots' of land degradation are present. In addition, deforestation and mismanagement were specifically not included in this study.

## APPENDIX R

### THE HARVEST INDEX AND THE POTENTIAL TO INCREASE MAXIMUM YIELDS

The increase in yields in the last decades has been the result of a combination of factors. The basis for this increase has been the use of better varieties with several advantages such as decreased sensitivity to day length, increased responsiveness of hybrids to fertilizer and to water and increased harvest indexes (HI). In fact, most of the increase in cereal yields has come from increasing HI's due to the introduction of dwarfing genes (resulting in shorter stem height). The overall photosynthetic efficiency is constant and total biomass production has changed little (Evans 1998). The most modern varieties of both rice and wheat have HI of 0.50 – 0.55 (Evans 1998). Current cereal HI's are 0.4 to 0.45, traditional varieties have a HI or 0.2 to 0.3 (FAO 2000b).

High yielding varieties are also very responsive to other factors such as the use of fertilizers and water availability. The use of these better varieties opened up the possibilities of increasing yields, but would not have been possible without the availability and use of cheap nitrogenous fertilisers, new herbicides and investments in irrigation (Evans 1998). The difference in productivity between different varieties as indicated by the FAO is very large. An average difference of 40% productivity between low and high producing varieties (based on average of all maximum attainable crop yield ranges, average of 1960 and 1996) and more than 100% for cereals (FAO 2002b).

The main boost in yields due to these developments occurred in the '70's and '80's and has been named the Green Revolution. The Green Revolution undoubtedly helped to improve nutrition throughout the world. Life expectancy in lesser developed countries increased by 10 years in two decades (from less than 43 years in the early 1950's to over 53 years in the early 1970's), with a major portion of the increase attributable to improved nutrition. Presently, the growth in cereal yields as observed in previous decades seems presently to level off (Luyten 1995; FAO 2000a)[37]. This phenomenon has been frequently debated in literature as a potential indicator that yield levels have reached maximum levels (in high input systems). In the period 1986 – 1998 much of the increase in yields has been the prolonged effect of the Green Revolution (Evans 1998).

The question arises what may be the potential to increase yields further in high input production systems. The strong increase in yields in the past decades has resulted in decreasing world food prices in the last decades. A consequence of these low price levels, investments in research and development are falling because they are becoming less profitable (IFPRI 2001c), which will have an impact on yield increases on the long term. An other effect of low food prices is that this is reflected in reduced use of inputs like fertiliser (Pinstrup-Andersen 1999), but also the use of other productivity increasing factors (use of machinery and chemicals) is likely less profitable. Since food prices are expected to remain stable or fall slightly at least to 2020, this situation is likely to remain for some time. On the long term, this may reduce future increases in yields. However, the most optimistic projections indicate that there is still considerable potential to increase productivity (theoretically and technically), even in the industrialised countries. According to Evans (1998) even in these high productive systems, there is much room for increasing yields since the maximum HI achievable through plant breeding is estimated for cereals at ca. 0.65 (Evans 1998). Duwayri (1999) states that the theoretical maximum yield level for rice is ca. 20 ton $ha^{-1}$ (Duwayri *et al.* 1999). On experimental stations, yields of 17 ton $ha^{-1}$ in

[37] Cereals are often taken as a reasonable proxy for global food supply.

the subtropical climate and 10 ton $ha^{-1}$ in the tropics have been reached. In the Philippines breeding efforts have resulted in the varieties with a annual production of 15 t dw $ha^{-1}$, compared to the usual 11 t dw $ha^{-1}$ and using less fertiliser and suitable for saline conditions (IFPRI 2001a).

## Appendix S

## Standing forest resources

A (potentially) large source of wood is the use standing stocks through partial removal of trees or full deforestation. Figures for volumes standing stock, current deforestation rates and theoretical supply of wood from deforestation are shown in table 15.

*Table 15.* Standing volume of forests and present deforestation rates, excluding protected areas ((un)comm. sp. = (un)commercial species). Source: (FAO 1998b, 2001).

| Region | Standing volume Comm. sp. (billion $m^3$) | Standing volume Uncomm. sp. (billion $m^3$) | Standing volume All sp. (billion $m^3$) | Deforestation rate (% yr-1) | Wood from deforestation Comm. sp. (million $m^3$) | Wood from deforestation Uncomm. sp. (million $m^3$) | Wood from deforestation All sp. (million $m^3$) |
|---|---|---|---|---|---|---|---|
| North America | 54 | 0 | 54 | 0.08 | 0 | 0 | 0 |
| Oceania | 7 | 1 | 8 | -0.15 | 12 | 2 | 14 |
| Japan | 3 | 0 | 3 | 0.01 | 0 | 0 | 0 |
| Western Europe | 13 | 1 | 14 | 0.28 | 0 | 0 | 0 |
| East Europe | 5 | 0 | 6 | 0.21 | 0 | 0 | 0 |
| C.I.S. and Baltic States | 85 | 0 | 85 | 0.08 | 0 | 0 | 0 |
| sub-Saharan Africa | 15 | 27 | 42 | -0.79 | 130 | 234 | 364 |
| Caribbean & Latin America | 39 | 67 | 106 | -0.47 | 204 | 349 | 553 |
| Near East & North Africa | 2 | 0 | 2 | 0.22 | 0 | 0 | 0 |
| East Asia | 19 | 4 | 22 | -0.16 | 34 | 6 | 40 |
| South Asia | 2 | 1 | 3 | -0.13 | 3 | 2 | 5 |
| World | 289 | 58 | 347 | -0.24 | 770 | 154 | 977 |

The largest potential of standing stock can be found in the Caribbean & Latin America, C.I.S. & Baltic States and sub-Saharan Africa. The C.I.S. & Baltic States stands out as the region with the largest stock of commercial species. The data also indicate that *in theory* deforestation contributes significantly to the global wood supply, although in reality much of this wood is not utilised. It can be concluded that the current standing stock (equal to 2011 EJ bioenergy) is a large reservoir of bioenergy.

## APPENDIX T

### ENERGY CONSUMPTION SCENARIOS

Three scenarios for total demand for primary energy are included in this study. All three scenarios are based on the report 'Global Energy Scenarios to 2050 and Beyond (WEC 1998a). The three scenarios are:

- high growth scenario. A world in which economic growth, energy consumption increases and energy efficiency improvements are strong.
- medium scenario. A middle coarse scenario, reference or middle-of-the-road evolution, but not simply business as usual.
- ecologically driven scenario. In this scenario policy makers and other actors in society succeed in promoting energy efficiency, technology innovation and transfer, non-fossil fuel development, and the reduction of institutional barriers. This scenario has the lowest energy consumption and greenhouse gas emissions trajectories.

The high, medium and low scenarios are based on the *relative annual increase* in consumption as projected in the A3, B and C1 WEC scenarios respectively, data are obtained via the online database (WEC 1998b). Country specific base year data are derived from the IEA database (IEA 2002a) and regionally aggregated. Note that the regional breakdown used by the WEC is slightly different from the one used in this study. As a result the results differ considerably from the original WEC scenarios. Therefore, the results are upscaled so that these match the total energy demand of the WEC scenarios.

These three scenario were chosen because:

- the three scenarios represent the range projected by other scenarios as well (see figure 9). The exception is the A1 IMAGE scenario, which as a 35% higher total primary energy use.
- the three scenarios go to 2050 (not all other scenarios do).
- the three scenarios are based on the a the same population growth scenario. The population growth in all three scenarios is higher the medium population scenario of the UNPD: 10.1 billion people in 2050 vs. 8.8 billion in the medium scenario. The high and low UNPD projection are 10.5 billion and 7.3 billion. Other scenarios vary often on population growth or more factors, making interpretation of the scenarios more difficult. The classification medium (most likely), high and low scenario is also used for other parameters in this study. The medium scenario may be considered as a medium scenario, the high and low scenario are described as the high growth and ecologically driven scenario. Note that the medium scenario is also very similar to the IEA projection to 2030.

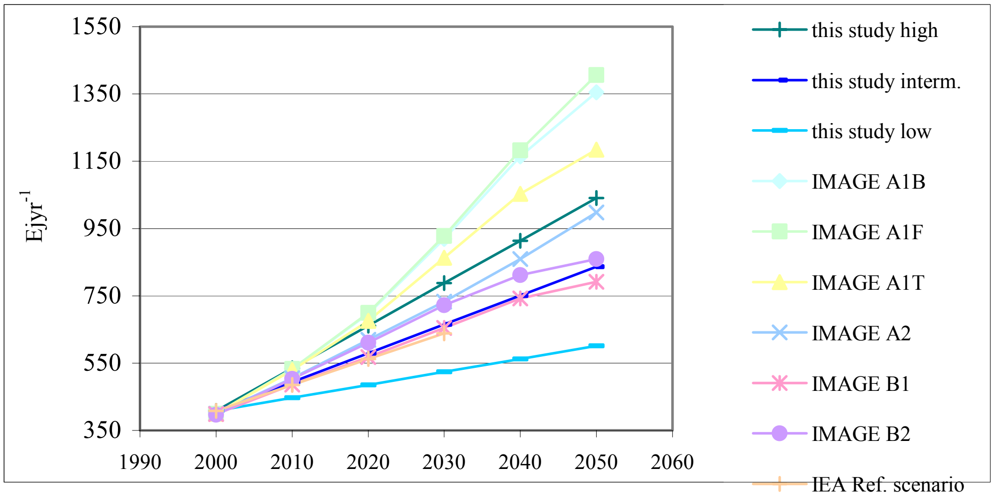


*Figure 9*. Comparison of scenarios of primary energy supply. Sources: (WEC 1998a; IMAGE-team 2001; IEA 2002b), own calculations.

Note that the different scenarios include the use of non commercial biomass, because it was not possible to exclude traditional biomass from the datasets. The bioenergy potential as a share of the total energy demand is thus underestimated, since the use of traditional biomass use is included in the forest products analysis.