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Yield trends and yield gap analysis of major crops in the world

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Abstract
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This study aims to quantify the gap between current and potential yields of major crops in the world, and the production constraints that contribute to this yield gap. Using an expert-based evaluation of yield gaps and the literature, global and regional yields and yield trends of major crops are quantified, yield gaps evaluated by crop experts, current yield progress by breeding estimated, and different yield projections compared. Results show decreasing yield growth for wheat and rice, but still high growth rates for maize. The yield gap analysis provides quantitative estimates of the production constraints for a number of crops and regions and reveals the difficulty to measure and compare yield potentials and actual yields consistently under a range of environmental conditions, and it shows the difficulty to disentangle interacting production constraints. FAO yield growth projections are generally lower than what possibly could be gained by closing current yield gaps.

Key words: potential yields, actual yields, yield constraints, food production, crop modelling

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Woord vooraf

Met de stijging van de voedselprijzen in 2007 en het debat over de mogelijke rol van biobrandstoffen hierbij is de aandacht voor het voedselvraagstuk en de draagkracht van de aarde voor de productie van plantaardige biomassa weer opgelaaid. Centrale vraag in veel analyses betreft de omvang en aard van de kloof tussen de huidige en potentiële gewasopbrengsten. Wat verklaart deze kloof en – vooral – wat kunnen we doen om deze kloof te overbruggen. Het Planbureau voor de Leefomgeving heeft Plant Research International gevraagd zich over deze vraag te buigen. Achtergrond van de vraag is te onderzoeken welk deel van de kloof kan worden toegerekend aan factoren die met gericht beleid kunnen worden verbeterd. Met andere woorden, waar kunnen opbrengststijgingen worden geëntameerd? Het huidige rapport doet verslag van dit project.

Uitgaande van de arealen van de belangrijkste gewassen in elf regio's zijn zowel huidige als potentiële opbrengstniveaus berekend voor de meest relevante gewas–regio combinaties. Een vijftal factoren is geïdentificeerd dat het verschil tussen potentiële en huidige gewas-opbrengsten kan verklaren: tekorten aan water, aan nutriënten, schade door ziekten en plagen, gebrekkige inzet van arbeid of machines, of gebrek aan kennis. De bijdrage van deze factoren aan de huidige opbrengstkloof is gekwantificeerd op basis van de inzichten en kennis van een aantal vooraanstaande internationale gewasdeskundigen. Hen is gevraagd het belang van verschillende verklarende factoren aan te geven.

Deze analyse, die uniek is zowel qua opzet als uitvoering, is van belang om een drietal redenen. Allereerst de veelomvattendheid: de belangrijkste gewassen voor elf mondiale regio's. Verder de beperkende factoren, die zowel biotische als abiotische elementen omvatten, alsook zaken die te maken hebben met gebruik en beschikbaarheid van kennis. Ten slotte ligt het belang in de inzet van vooraanstaande gewasdeskundigen. Hun ervaring wordt gebruikt bij het in kaart brengen van de opbrengstkloof en verkennen van de mogelijkheden deze te verkleinen. Dit geldt zowel voor belangrijke voedselgewassen (granen) als eiwit- en industriegewassen, en richt zich op ontwikkelde landen zowel als ontwikkelingslanden. Bij het schatten van mogelijke opbrengststijgingen wordt ook gekeken naar de gevolgen van plantenveredeling voor de opbrengststijgingen.

Wij zijn de deskundigen dankbaar voor hun bereidheid aan deze lastige oefening mee te werken. Ook willen we onze dank betuigen aan onderzoekers die ons voorzien hebben van tips op zowel theoretisch/conceptueel gebied als bij praktische zaken. De verantwoordelijkheid voor de analyse ligt uiteraard volledig bij ons.

Huib Hengsdijk
Hans Langeveld

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Summary

Relationships between the demand for biomass, greenhouse gas emissions, food prices, biodiversity and poverty are poorly understood. Modelling is used to quantify and better understand these relationships. The Integrated Model to Assess the Global Environment (IMAGE) developed under the authority of the Netherlands Environmental Assessment Agency (PBL) evaluates policy options related to combat climate change, biodiversity conservation and development. Current crop yields used in the model are, however, outdated and require actualization. Further, PBL wants to improve its insight in future productivity change and the way policies can reduce the gap between current and potential yields. Better insight in the yield gap and its underlying constraints is crucial to help define, assess or evaluate measures aimed at stimulating agricultural production and rural development including combating malnutrition and hunger. This study aims to improve this insight by evaluating the current yield gap of major crops and associated production constraints based on knowledge of crop experts.

Central in the study is the question which production constraints can explain the current yield gap for major crops. Explaining constraints include: (i) shortages of nutrients, (ii) of water, (iii) damage due to pests, weeds and diseases, (iv) insufficient or improper application of labour or machines, and (v) lack of knowledge. These constraints are interrelated, but in the approach it is not possible to identify or account for all possible interactions.

Crop areas have been identified for sixteen major crops, including cereals (wheat, barley, maize, rice, tropical cereals), pulses (soybean, dry bean, groundnut), root and tuber crops (potato, cassava), oil crops (rape seed, sunflower, oil palm) and other industrial crops (cotton, sugar cane, sugar beet). Regions defined for this study include Central and South America North America, Semi-arid West Asia and Africa, Humid Africa, Western Europe, Central and Eastern Europe, Commonwealth of Independent States, North East Asia, South East Asia, Southern Asia, and Oceania. A selection of the most relevant crop-region combinations was made to limit the number of possible crop-region combinations to 57.

In the study, the following yield levels are identified: actual farm yields and potential yields. Actual yields were derived from crop statistics and estimates of potential yield were based on the IMAGE model. Some of the consulted crop experts provided alternative estimates for these potential yields.

For each crop, global trends in cultivated area and actual yields were calculated in order to analyse historical production dynamics. Results suggest that the grain maize area increased most strongly, surpassing the global paddy rice area in 2007. Tropical cereals (sorghum), wheat and barley show area decreases, while oil crops (i.e. soybean and oil palm) show a steady area increase. Yield trends show a highly varying picture, with strong cereal yield increases in the 1970s and 1980s followed by periods of reduced growth rates since 1990. Yield levels of oil crops seem to accelerate; root and tuber crops taking an intermediate position.

Regional yield trends were calculated for wheat, maize, and rice. Results for wheat are highly variable, but show a clear trend with declining yield increases in industrialized countries as well as developing countries. However, the latter maintain a slightly higher growth rate. In absolute terms, historical annual improvement, after higher initial figures, appears to level out at annual

increases of less than 50 kg/ha/y in all regions except for Eastern Asia showing an increase of 75 kg/ha/y.

Results for other cereals are distinctively different: recent progress in maize yields exceeds that of wheat and in many regions varies between 2 and 3%, and an impressive 3.3% in Southern America as outlier. Progress in rice yields is mixed, Eastern Asia now showing increases of less than 0.5% per year, while annual increments in less productive regions of South Eastern and Southern Asia are 1.5% or higher.

We approached 23 crop experts to quantify the relative contribution of the five production constraints to yield gaps. Over 60% of them replied, but only few were able to provide such quantitative estimates. Most experts limited themselves to qualitative estimates, sometimes providing quantitative yield loss estimates using different conceptualizations. Additional information was taken from the literature, e.g. referring specifically to yield losses due to pests, weeds and diseases, or to specific crops in given regions.

Results show that there still is a large confusion with respect to the yield gap concept, some experts focus mainly on theoretical potential levels as determined by crop growth models. Others focus on economically attainable yield levels defined as highest yields realized by farmers under favorable socio-economic conditions. These yield levels seem to correspond with around 70-80% of the yield potential.

Some of the potential yields estimated by the experts differed from the values calculated by the crop model of IMAGE. Especially for maize and potato, IMAGE potential levels appear to remain below expert potential estimations. This problem was already acknowledged by IMAGE researchers, and in fact was one of the reasons why currently a new crop model is being implemented in IMAGE. Further problems include the need to come to generic yield gap analyses for given regions. This sometimes forced experts to combine results from specific cropping systems. As growing conditions show large variations among cropping systems, this automatically lead to generalizations where experts would have preferred specific estimations.

The yield gap analysis suggests that in more advanced economies, where crop levels approach economically attainable yield levels, non-technical factors such as deficiencies in knowledge systems become more important. This is explained by the fact that abiotic (water and nutrients) and biotic (crop protection) constraints in these regions are better dealt with. In situations where yield gaps are large, still considerable yield gains can be made by improving access to and availability of water, nutrients and crop protection agents. One clear exception to this rule is the potato yield gap in Western Europe mainly suffering from water shortages. Unclear is whether this is a methodological/expert bias or indicates at a crop-specific exception.

A comparison of yield losses reported by experts with respect to pests, weeds and diseases with those listed in the literature, suggests that the former tend to specify lower losses. This may be explained by the fact that they also need to consider yield depression by shortages of water or nutrients and, thus, underestimate losses due to biotic constraints.

Current progress in yield potential due to breeding is estimated in the literature at 0.5% per year for wheat and rice, and about 1% per year for maize. Hybridization may provide a one-time yield boost of 10-15% compared to best inbred varieties. For a number of crop-region combinations, the collected information on yield levels, yield gaps and progress in yield potentials has been used to assess the FAO yield projections as used in IMAGE. In general, these projections are lower than what possibly could be gained by closing current yield gaps.

If progress in breeding can be maintained at current levels, various yield gaps even appear to increase over time. This means that exploitable yield gaps remain large, which is deemed necessary to maintain growth in average farm yields. However, the combined effect of the stagnating or even negative growth of farm yields of major cereals (e.g. of wheat) presented here as well as reductions in production area in relation to the increasing global food and biomass demand is alarming. The analysis indicates that yield growth rates in major wheat and rice growing regions are declining. Growth rates of maize are still high in most regions but a major part of the maize production is used for livestock and biofuel production and not for direct consumptive purposes.

With almost 60% of the contacted experts replying, few provided quantitative estimates of the yield constraining factors required for a comprehensive explanation of existing yield gaps. This seems to confirm the fact that such an analysis is challenging. Both the responses and the fact that similar exercises are currently being (or have recently been) conducted (e.g. by the International Rice Research Institute and the Generation Challenge Program of CGIAR) shows the relevance of the work presented here. The majority of the work has been carried out for wheat, maize and rice, skewing responses and data availability of our study. Although understandable in the light of cereal food crop dominance, it seriously limits options to evaluate perspectives for crop diversification which may be needed to satisfy the future demand for multiple crop uses for food as well as feed and fuel.

In conclusion, our analysis provides an overview of yield trends of major food and industrial crops. It defines actual yield gaps, contributes to the knowledge base on yield measures, and assesses the relevance of production constraints, technical as well as non-technical. Prominent crop experts have provided their insights and shared their knowledge and data. The study especially reveals the difficulty to measure and compare yield potentials and actual yields consistently under a range of environmental conditions, and it shows the difficulty to disentangle interacting production constraints.

1 General introduction

1.1 Background

Demand for biomass has strongly increased due to population growth, increasing economic welfare and need for sustainable feedstocks to replace fossil fuels (FAO, 2008). The increased demand for biomass claims additional resources and has been linked to higher commodity prices (Rosegrant, 2008), increased poverty (Von Braun, 2008), and land use change (Morton *et al.*, 2006; Searchinger *et al.*, 2008). The relationships among the demand for biomass, greenhouse gas emissions, food prices, biodiversity and poverty are complex and poorly understood. Modelling approaches are required to quantify and better understand these relationships. One of such modelling approaches is the Integrated Model to Assess the Global Environment (IMAGE) developed under the authority of the Netherlands Environmental Assessment Agency (PBL). IMAGE is an ecological-environmental framework that simulates the environmental consequences of human activities worldwide. It represents interactions between society, the biosphere and the climate system to assess sustainability issues like climate change, biodiversity and human well-being.

A crucial element in IMAGE and other global assessment models is the change in agricultural productivity as this determines the global demand for agricultural land in the future. If crop yields can be doubled, only half of the land is required for agriculture assuming the same demand for agricultural products.

Productivity change in agriculture is an autonomous process but it can be accelerated by coherent and enabling Government policies as witnessed during the Green Revolution. However, productivity gains in agriculture are unequal in time and space. Growth in agricultural productivity has been virtually absent in many parts of sub Saharan Africa over the last decades (Rabbinge *et al.*, 2004). In other parts of the world, further gains in the agricultural productivity are questioned as yields of many crops are already high (Calderini and Slafer, 1998; Cassman, 2001).

Progress in productivity and the yield gap, i.e. the difference between potential crop yields based on theoretical knowledge of relevant agro-ecological production processes and the yields as obtained by farmers in practice have been subject of debate (e.g. Tilman *et al.*, 2002; Ruttan, 2005). Conflicting estimations call for an assessment of potential global crop yield increases and of those factors hindering productivity gains in different parts of the world. A better insight in the yield gap and the underlying factors is a crucial source of information for those that want to define, assess or evaluate measures aimed at stimulating agricultural production and rural development including combating malnutrition and hunger.

1.2 Objectives

The objectives of this report are (i) to quantify the gap between current and potential yields for major crops and regions in the world, (ii) to quantify production constraints that contribute to the current yield gap.

The report addresses the following questions:

- What are the current yields of major crops in different parts of the world?

- What has been the yield increase of major crops in different parts of the world during the last decades?
- What are the potential yields of major crops in different parts of the world?
- What is the contribution of different production constraints to the yield gap of major crops in the world?
- What is the expected progress in yield potentials of crops through breeding?

1.3 Scope of report

Agricultural intensification in IMAGE is mainly described on the basis of growth projections by the Food and Agriculture Organization (FAO) and the expected intensification as projected by the agro-economic models such as the General Trade Analysis Project (GTAP) and International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT). Although insights in the increase in agricultural productivity crucial is for estimating the future demand of agricultural land, knowledge of the driving forces and trends of agricultural intensification is until now incomplete in these models and often treated using 'management' factors. This approach is less appropriate for estimating yield potentials, costs and impacts and the economic implications of different means of intensification such as improved crop varieties, irrigation, mechanization and improved nutrient management as there may be large differences among regions and crops. This report aims at making the different production factors contributing to the yield gaps more explicit for different crops and regions. Results of the study are meant to support the modeling framework of IMAGE. Therefore, IMAGE conventions and classifications have been used in the study if possible.

1.4 Outline of report

In Chapter 2 the used data and methods are described. Emphasis is on the selection of crops and regions, definition of used yield measures in this study and the expert-based evaluation of yield gaps including a description of the production constraints that have been taken into account. Chapter 3 presents the results roughly addressing global and regional yields and yield trends, the yield gap analysis, current yield progress as a result of breeding, and yield projections based on the collected information and the FAO projections used by the IMAGE model. Chapter 4 discusses the results and concludes on the specific topics related to yield growth, potential yield levels (as used in this study), the expert-based evaluation of yield gaps and the analysis of the yield projections.

2 Material and Methods

Basically, three approaches have been used to realize the objectives of the study. The statistical database of the Food and Agriculture Organization (FAO) FAOSTAT (http:\\faostat.fao.org) has been used to identify major crops, to quantify current crop yields and productivity trends of major crops in different parts of the world. Potential yields of major crops in different parts of the world have been derived from IMAGE. These yields have been used to estimate the current yield gap for a selected number of crop-region combinations. The contribution of various production factors to the current yield gap has been estimated through a dedicated survey under crop specialists. In the remaining part of this chapter the various approaches are described in detail.

2.1 Crop and regional selection

The analyses have been carried out for a selection of crops ('major crops') and regions. In the yield gap analysis only those region-crop combinations are considered that satisfy together at least 90% of the total area of major crops in a region.

2.1.1 Crop selection

Crops included in the analysis were selected using the following criteria: cultivated area, role as basic food or feed crop, relevance for industrial production, relevance for bioenergy feedstock and relevance for location-specific cropping systems:

- Cultivated area: *rice, wheat, maize;*
- Relevance for food consumption (staple food or diet): *rice, wheat, maize, barley, potato, pulses; cassava;*
- Relevance as industrial crop: *sugar cane, sugar beet*; *cotton;*
- Relevance for (future) biofuel production (bioethanol, biodiesel, biogas): *maize, sunflower, soybean, rape seed, oil palm, sorghum, sugar beet, sugar cane;*
- Relevance for specific cropping system or region: *millet, dry beans, cassava*.

Obviously, some crops satisfy various selection criteria simultaneously, while other crops only one criterion. An overview of globally cultivated areas of these crops is presented in Table 2.1. Major food crops include three dominant cereals (wheat, rice and maize) each cultivated on 150 million hectare (Mha) or more. Of the other food crops, barley is the only crop grown on more than 50 Mha. Soybean, groundnuts (in tropical lowlands) and dry beans (temperate and tropical areas) are dominant pulses. Soybean covers almost twice as much land as groundnuts and dry beans together, but it is mostly used as animal feed. Root and tuber crops potato and cassava are cultivated on nearly 20 Mha each. Other relevant crops for future biofuel production include sugar cane (21 Mha), rape seed (29 Mha), oil palm (14 Mha) and sugar beet (5 Mha).

Together, the crops included in Table 2.1 cover almost 950 Mha, or 78% of arable crops globally cultivated, the remainder being fruits and vegetables (65 Mha) and minor crops (mainly oats, rye, cowpeas, coconuts, peas, chickpeas, sweet potatoes, yams, other root and tuber crops).

Table 2.1 Major crops cultivated worldwide

Name	Crop type, use	Cultivated area (Mha)[1]
1. Wheat	Cereal, staple food, animal feed	216
2. Rice, paddy	Cereal, staple food	157
3. Maize	Cereal, staple food, animal feed	152
4. Soybean	Oilseed, pulse, animal feed	95
5. Barley	Cereal, staple food, animal feed	57
6. Sorghum	Cereal, staple food, animal feed	44
7. Millet	Cereal, staple food, animal feed	36
8. Cotton, seed	Fibre, oilseed, animal feed	34
9. Rape seed	Oilseed	27
10. Dry beans	Pulse	27
11. Groundnut	Oilseed, pulse	23
12. Sunflower	Oilseed	22
13. Sugar cane	Industrial crop	21
14. Potato	Tuber crop, staple food	19
15. Cassava	Root crop, staple food, animal feed	19
16. Oil palm	Oilseed	14
17. Sugar beet	Industrial crop	5

[1] Source: FAOSTAT (http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor), visited 27 January and 27 April, 2009.

IMAGE identifies 19 crop groups of which seven are irrigated crop groups: temperate cereals, rice, maize, tropical cereals, pulses, roots and tubers, and oil crops. Table 2.2 shows the matching of IMAGE crop groups and the selected crops in this study. Cotton seed, sugarcane and sugar beet do not match well with one of the seven IMAGE crop groups. To increase consistency with the IMAGE crop groups, millet and sorghum have been grouped together under tropical cereals in the remainder of the report. Hence, a total of 16 crops are considered in the analysis.

Table 2.2 IMAGE irrigated crop groups and crops included in this study.

IMAGE crop group	Crops in this study
Temperate cereals	Wheat, barley
Rice	Rice
Maize	Maize
Tropical cereals	Sorghum, millet
Pulses	Soybean, dry beans, groundnut,
Roots and tubers	Cassava, potato
Oil crops	Rape seed, sunflower, oil palm
Other crops	Cotton seed, sugarcane, sugar beet

2.1.2 Regional selection

Estimation of yield gaps, identification of production constraints and future yield potentials for individual crops require a thorough knowledge of natural resources (soils, climate) and crop production systems. Generally, the more uniform the regions that are considered, the better the outcome of the analysis. A detailed analysis of crop production conditions in a large number of countries is, however, beyond the scope of this study.

It was decided to select a limited (10-15) number of geographical regions showing major similarities with respect to agro-ecological (climate, soils, major crops, water availability) as well as economic (income levels, economic and infrastructural development) conditions. Regions were selected in such way to allow optimal use of available (statistical) data on natural resources and crop production. Finally eleven regions were selected; they are based in the Americas (2), Eurasia (3), Asia (3), Africa (2) and the Australia/Pacific region (1) (Table 2.3).

Table 2.3 Regions included in this study.

Region	Relevance	Remarks
1. Middle and south America, Caribbean	Large region with high production potentials, including major agricultural producers. Some are dominant or promising biofuel producers.	Emerging economies. Major wheat, maize, soya, potato, sugar cane and grassland region.
2. North America	Large region with highly productive agriculture. Includes dominant bioethanol producer (USA) and major feedstock producer (Canada).	Industrialised economies. Major maize, soya and wheat regions.
3. Semi-arid West Asia and Africa	Large agricultural area with low production potentials, including the Middle East, Turkey and countries of North, West and Southern Africa. High population growth.	Major wheat, barley, pulses, cotton and cassava region. Major (sub-) tropical grassland region.
4. Humid Sub-Saharan Africa	Very large region with currently low yielding but potentially important commodities. High population growth.	Major tropical maize, cereals, beans and cassava regions.
5. Western Europe	Small region of intensively cultivated highly productive countries, includes dominant biodiesel production.	Major wheat, barley, potato, beet, rape and grassland region.
6. Central and Eastern Europe	Moderately productive region with vast agricultural potential.	Major maize region.
7. Common wealth of Independent States (CIS)	Former Soviet Union. A large region with large agricultural areas at low to moderately productivity.	Major maize and cotton region.
8. Northeast Asia	Large region including large number of people population. Moderately productive with moderate to low potential.	Major rice, wheat, soya and temperate grassland region.
9. South Asia	Major area of low productive rice/wheat systems including India and Pakistan. Large population in high densities.	Major tropical cereals and pulses region. Includes India.
10. Southeast Asia	Including the major alluvial plains of Asia and the Far East. Moderately to highly productive region with considerable potential.	Major rice and oil palm area. Southeast of China.
11. Australia, New Zealand and Pacific	Extensive, dispersed, region of low to highly productive land. Vulnerable to climate change.	Major wheat region.

The IMAGE framework subdivides the globe into 24 regions. In Table 2.4 the IMAGE classification is compared with the regional division used in this study.

Table 2.4 Comparison of the IMAGE regions and the regional division used in this study.

IMAGE regions	Regions in this study	Comments
(3) Mexico, (4) rest of Central America, (5) Brazil, (6) rest of south America	1. Middle and south America, Caribbean	Aggregation of four IMAGE regions
(1) Canada, (2) USA	2. North America	Aggregation of two IMAGE regions
(7) Northern Africa, (8) Western Africa, (9) Eastern Africa, (10) Middle East,	3. Semi-arid areas of West Asia and Africa	Only arid areas of Africa
(11) Southern Africa, (8) Western Africa, (9) Eastern Africa	4. Humid Sub-Saharan Africa	Includes also humid areas of Western and Eastern Africa
(12) OECD Europe	5. Western Europe	
(13) Turkey, (14) Central Europe	6. Central and Eastern Europe	
(15) Ukraine, (16) Asia-Stan, (17) Russia	7. CIS	Roughly aggregation of three IMAGE regions
(18) Korea, (19) Japan, (22) China	8. Northeast Asia	Includes also the North China Plain
(22) China, (21) India	9. South Asia	(sub) Tropical parts of China
(23) South-eastern Asia, (20) Indonesia	10. Southeast Asia	Roughly aggregation of two IMAGE regions
(24) Oceania	11. Australia, New Zealand and Pacific	

Major differences in the regional classifications relate to Africa and Asia. In our classification the semi-arid areas of Africa and West-Asia (Middle East) are grouped together; In the IMAGE classification West-Asia corresponds mostly with the separate region Middle East, while Africa is subdivided into four regions along the four quarters of the world. Humid Sub-Saharan Africa, identified in this study, includes humid areas of East, West and Southern Africa. Ukraine is included in Eastern Europe in our study, not in CIS. The latter also includes Armenia, Azerbeidjan and Georgia. Our Northeast Asia region, further, includes parts of the North China Plain (roughly between 114 and 121 °E, and 32 and 40°N) in addition to the IMAGE regions Japan and Korea. South Asia includes the (sub)tropical parts of China. In IMAGE, China is considered a separate region

2.2 Current crop yields, and area and yield changes

Current global crop yields are based on FAOSTAT data and comprise three-year averages for 2005-2007. Global changes in cultivated area and yield of the 16 major crops are also based on FAOSTAT and cover the period 1961-2007. Global crop yield and area changes are analysed by comparing the average yields and areas, respectively, in four periods, i.e. 1961-1969, 1970-1979, 1980-1989, 1990-1999 and 2000-2007 with the average yields and areas in the previous period.

Regional changes in yield of wheat, maize and rice are analysed using FAOSTAT data. This analysis is done for major growing regions for wheat, maize and rice and it provides insight in the regional yield trends. Note that the regional crop yields are based on the regional classification as used by FAOSTAT. Table 2.5 provides a comparison of the 18 FAOSTAT regions and the 11 regions used in this study.

Table 2.5 Comparison of the 18 FAOSTAT regions and 11 regions used in this study.

FAOSTAT regions	**Regions in this study**
1. Eastern Africa (EAfrica)	3. Semi-arid areas of West Asia and Africa
2. Middle Africa (MAfrica)	4. Humid Sub-Saharan Africa
3. Northern Africa (NAfrica)	3. Semi-arid areas of West Asia and Africa
4. Southern Africa (SAfrica)	4. Humid Sub-Saharan Africa
5. Western Africa (WAfrica)	3. Semi-arid areas of West Asia and Africa
6. Northern America (NAfrica)	2. North America
7. Central America (CAmerica)	1. Middle and south America, Caribbean
8. South America (SAmerica)	1. Middle and south America, Caribbean
9. Central Asia (CAsia)	7. CIS
10. Eastern Asia (EAsia)	8. Northeast Asia
11. Southern Asia (SAsia)	9. South Asia
12. South-Eastern Asia (SEAsia)	10. Southeast Asia
13. Western Asia (WAsia)	3. Semi-arid areas of West Asia and Africa
14. Eastern Europe (EEurope)	6. Central and Eastern Europe
15. Northern Europe (NEurope	5. Western Europe
16. Southern Europe (SEurope)	5. Western Europe
17. Western Europe (WEurope)	5. Western Europe
18. Australia and New Zealand (Aus)	11. Australia, New Zealand and Pacific

2.3 Yield definitions

We use two yield definitions, i.e. average farm yield and potential yield. The average (farm) yield is the average yield achieved by farmers in a defined region and period. We used FAOSTAT to estimate average farm yields for the period 2005-2007. The potential yield is defined as the maximum yield of a crop cultivar grown in an environment to which it is adapted, with nutrients and water non-limiting and pests and diseases effectively controlled (Evans and Fischer, 1999). In general, maximum potential yields can be estimated using results of highly controlled on-station experiments or crop models calibrated using crop characteristics of the latest varieties (Fischer *et al.*, 2009). In our case we used estimates of potential crop yields as simulated by the IMAGE model in the Global Agro-ecological zoning project (GAEZ). The GAEZ methodology matches requirements of land use types with environmental requirements and then calculates biomass and yields as determined by radiation and temperature- via the method of Kassam (1977).

2.4 Yield gap analysis

2.4.1 Crop-region combinations

The yield gap analysis, i.e. the difference between current average farm yields and potential yields (Section 2.3) has been carried out for a selected number of crop-region combinations (Table 2.6). Only the most important combinations were selected, including those combinations that cover at least 90% of the cultivated area (based on the 16 crops used in this study). Consequently, the yield gap analysis is not performed uniformly across crops and regions. For example, wheat is a dominant crop in nine regions, while groundnut, sugarcane and sugar beet are included in one region only (Table 2.6). Similarly, in the ANZ Pacific three crops cover 90% of the cultivated area, while in South Asia the cultivated areas of eight crops is required to realize a 90% coverage. In total 57 crop-region combinations were selected (Table 2.6).

2.4.2 Production constraints

Five production constraints have been identified that contribute to explaining the yield gap, i.e. (i) limited water availability, (ii) limited nutrient availability, (iii) inadequate crop protection (iv) insufficient or inadequate use of labour or mechanization, and (v) deficiencies in knowledge. Water shortages during the growing season can be reduced using irrigation; nutrient limitations can be lifted by applying organic or inorganic fertilizers. Yield reductions due to inadequate control of weeds, pests and diseases can be avoided by introduction of proper crop protection including the use of biocides, phytosanitary methods and crop rotations. Mechanization and labour can be substituted. Insufficient or inadequate application of labour and machinery may contribute to the current yield gap. Especially for operations where timeliness is crucial, such as sowing or planting, limited application may result in yield reductions, e.g. when delayed sowing is done under unfavourable weather conditions (e.g. Cirilo and Andrade, 1994). In other cases, seasonally-specific cultivation patterns may cause temporal labour shortages that, in their turn, reduce the adoption of new technologies (White *et al.*, 2005). In Africa, where many production situations are based on manual labour, the availability of labour may be limited during the period crucial for weeding. Under these conditions, poorly controlled weed populations may reduce crop yields (e.g. Riches *et al.*, 1997). The fifth production constraint explaining yield gaps refers to deficient knowledge resulting in inadequate crop management other than discussed above. This may affect crop yields in many ways, e.g. by applying poor quality seed or planting material, inappropriate plant densities, or by selecting poorly adapted crop varieties, damaging plants by inadequate applications of fertilizers or crop protection agents, etc. It may also include incorrect, premature or late harvesting, etc.

Obviously, these production constraints are interrelated and their effects difficult to separate. For example, weather conditions may limit the accessibility of fields to fertilizer application machinery, resulting in decreased nutrient availability and thus reduce crop yields. It is, however, not possible to identify or account for possible interactions and synergies and the production constraints are treated as independent constraints, each individually contributing to the yield gap in a particular region.

2.4.3 Expert-based evaluation of yield gaps

The relative contribution of production constraints contributing to the gap between potential and current yields differs among crops and regions. A dedicated questionnaire was therefore developed to allow crop experts to estimate the relative contribution of each constraint for selected crop-region combinations (Section 2.4.1). Annex I presents an example of the survey. A total of 23 key experts were approached by email with crop-specific surveys. The key experts included experienced crop specialists working in national and international research institutions.

Table 2.6 Regional crop area percentages and the total of these crop areas as percentage of total harvested crop area in a region. The bold numbers indicate the crop shares totaling 90% or more of the major crop areas in a region for which a yield gap analysis is performed.

Crop (group)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	
	Latin America	**North America**	**SA´s WAA**	**Humid SSA**	**W Europe**	**C & E Europe**	**CIS**	**NE Asia**	**S Asia**	**SE Asia**	**ANZ pacific**	**No. of regions**
Wheat	**8.1**	**25.8**	**34.0**	1.9	**42.1**	**32.8**	**58.7**	**23.6**	**21.0**	0.1	**63.3**	9
Rice	**5.4**		2.3	**8.9**	0.9	0.0	0.6	**32.8**	**32.3**	**63.0**	0.5	5
Maize	**25.1**	**28.8**	**7.9**	**29.0**	**9.4**	**18.3**	2.2	**27.9**	**5.3**	**12.1**	0.5	9
Soybeans	**36.5**	**27.4**	0.2	1.7	0.5	2.2	1.2	**9.8**	**4.4**	1.7		4
Barley	1.1	4.3	**14.3**		**26.1**	**17.7**	**16.4**	1.0	0.5		**23.0**	5
Tropical cereals	3.2	2.3	**30.9**	**27.5**		0.2	0.7	1.5	**11.5**	0.3	3.6	3
Cotton	1.9	**4.4**	**3.6**	2.8	0.9		4.0		**6.6**	0.4	1.5	3
Rape seed		**5.2**	0.1		**9.9**	**4.4**	0.8		**4.2**		**5.1**	5
Dry beans	**6.2**	0.7	0.8	**5.6**		0.4	0.1	1.6	**4.9**	3.5		3
Groundnut	0.4	0.4		**6.6**		0.4			3.5	2.4		1
Sunflower	2.4	0.8		1.0	3.3	**13.5**	**8.4**		1.4	0.8		2
Sugar cane	**8.4**		0.5	1.6				1.3	3.0	3.1	2.6	1
Potato	0.9	0.5	1.0	1.6	3.1	**7.0**	**5.0**		1.1	0.3		2
Cassava	2.6		0.1	**11.8**				0.3	0.2	**4.3**		2
Oil palm	0.5			**5.3**						**11.4**	0.0	2
Sugar beet		0.4	0.8		**3.8**	3.1	1.4	0.2				1
Area major crops (in bold) / area of all listed crops (%)	*90*	*92*	*91*	*95*	*91*	*94*	*93*	*94*	*90*	*91*	*90*	
Area major crops (in bold) / total regional harvested crop area (%)	*85*	*92*	*78*	*78*	*82*	*83*	*88*	*65*	*82*	*93*	*82*	
No. major crops per region	*6*	*5*	*5*	*7*	*5*	*6*	*4*	*4*	*8*	*4*	*3*	57

3 Results

3.1 Global trends in crop yields and areas

The change in the globally cultivated areas of major crops for the periods 1970-1979; 1980-1989; 1990-1999; and 2000-2007 are shown in Table 3.1.

Table 3.1 Average annual change in cultivated crop areas (%) in the periods 1970-1979; 1980-1989; 1990-1999; and 2000-2007 compared to the average cultivated area in the previous decade.

Crop	1970-1979	1980-1989	1990-1999	2000-2007
Wheat	0.4	0.3	-0.4	-0.4
Rice	1.0	0.4	0.3	0.3
Maize	1.0	0.6	0.7	0.7
Soybean	3.1	2.8	1.6	3.4
Barley	2.0	0.2	-1.5	-2.6
Tropical cereals	-0.1	-0.2	-0.7	-0.2
Cotton	0.4	-0.5	0.2	-0.1
Rape seed	2.9	3.4	3.6	1.7
Dry beans	0.0	0.9	-0.3	0.3
Groundnut	0.4	-0.2	1.2	0.7
Sunflower	2.5	3.0	2.8	1.2
Sugar cane	2.1	2.1	1.6	1.3
Potato	6.3	-0.8	0.0	0.5
Cassava	1.5	1.0	1.1	1.0
Oil palm	0.3	2.7	3.8	4.4
Sugar beet	1.0	0.4	-1.3	-4.6

From the cereal crops, the area with grain maize increases most rapidly. In fact, the global area with grain maize surpassed the area with paddy rice in 2007 (data not shown). The area with tropical cereals (sorghum) steadily decreased within the period 1961-2007 probably in favour of maize cultivation, especially in Sub-Saharan Africa. The cultivated area of two other major cereals, i.e. wheat and barley, also decreased since the 1990s.

The area expansions of soybean and palm oil are largest and mainly driven by the increased demand for livestock feed and oil for human consumption. The recent increased demand for oil-based biofuels may have further triggered the increased growth in oil palm area during the last decade. However, the increased attention in recent years for ethanol-based biofuel crops, i.e. sugar cane and sugar beet is not (yet) echoed in strongly increased crop areas of both crops. In contrast, the area with sugar beet has decreased most in 2000-2007 compared to the other crops.

Current yields and the change in yields of major crops in the periods 1970-1979; 1980-1989; 1990-1999; and 2000-2007 are shown in Table 3.2.

Table 3.2 Current crop yields (average 2005-2007), and the average annual change in crop yields (%) in the periods 1970-1979; 1980-1989; 1990-1999; and 2000-2007 compared to the average yields in the previous decade.

Crop	**1970-1979**	**1980-1989**	**1990-1999**	**2000-2007**	**Current yield (t ha^{-1})**
Wheat	2.4	2.2	1.7	0.9	2.81
Rice	1.6	2.1	1.5	1.0	4.12
Maize	2.3	1.8	1.4	1.7	4.86
Soybean	2.0	1.0	1.5	1.2	2.31
Barley	1.7	0.9	0.9	0.9	2.45
Tropical cereals	2.3	0.9	-0.3	-0.2	1.40
Cotton	1.1	2.2	1.0	1.9	2.07
Rape seed	2.4	2.9	1.4	1.9	1.73
Dry beans	0.8	0.7	1.2	1.1	0.71
Groundnut	0.8	1.5	1.6	2.0	1.55
Sunflower	0.2	0.9	-0.3	0.1	1.28
Sugar cane	0.6	0.8	0.6	0.6	68.19
Potato	9.2	0.3	0.5	0.8	16.76
Cassava	0.8	1.0	0.4	1.5	11.85
Oil palm	2.9	3.4	2.0	2.0	13.68
Sugar beet	1.4	0.9	0.7	2.3	46.75

Productivity growth of most crops decreases over the entire period 1970-2007 compared to previous periods, especially of cereals. The combined effect of low yield growth and decreasing cultivated areas of barley indicates that global production decreases. The growth in production of the major food staple wheat lacks behind the average global population growth of 1.3% in the period 1997-2007 (WHO, 2009).

However, these global productivity numbers hide a wide variation across regions, which is addressed in the following section for three major cereals, i.e. wheat, maize and rice.

3.2 Regional trends in crop yields

3.2.1 Wheat

Figure 3.1 shows the average annual percentage change of wheat yields for eleven major wheat growing regions covering more than 90% of the global wheat area in 2007. Figure 3.1a shows the average yield change of advanced economies, and Figure 3.1b the yield change of developing and emerging economies in four periods.

Both in the advanced economies and the developing and emerging economies yield growth decreases, though more pronounced in the former. Recent progress in wheat yields is less than 1% in the developing countries, while yields decreased in Australia and New Zealand compared to the last decade of the 20th century. In developing and emerging countries the yield growth varies roughly between 1 and 2% in the beginning of 21st century.

A percentage decrease in yield growth does not necessarily result in a yield decrease in absolute terms since 1% of 10 t/ha equals 2% of 5 t/ha. Therefore, absolute yield changes for the eleven regions over four periods are shown in Figure 3.2. Current yields (average 2005-2007) of the eleven regions are shown in Table 3.3. Figure 3.2 confirms more or less the trends shown in Figure 3.1 with a larger yield progress in developing and emerging economies than in advanced economies during the beginning of the 21st century. Especially, Northern and Western Europe, and Eastern Asia have shown impressive yield gains in the last century, but also in these regions yield progress sharply decreased (Northern and Western Europe) or has flattened (Eastern Asia) in the 21st century. Quite remarkably is the relatively low yield growth in North America, Australia and New Zealand in all four decades compared to the other advanced economies.

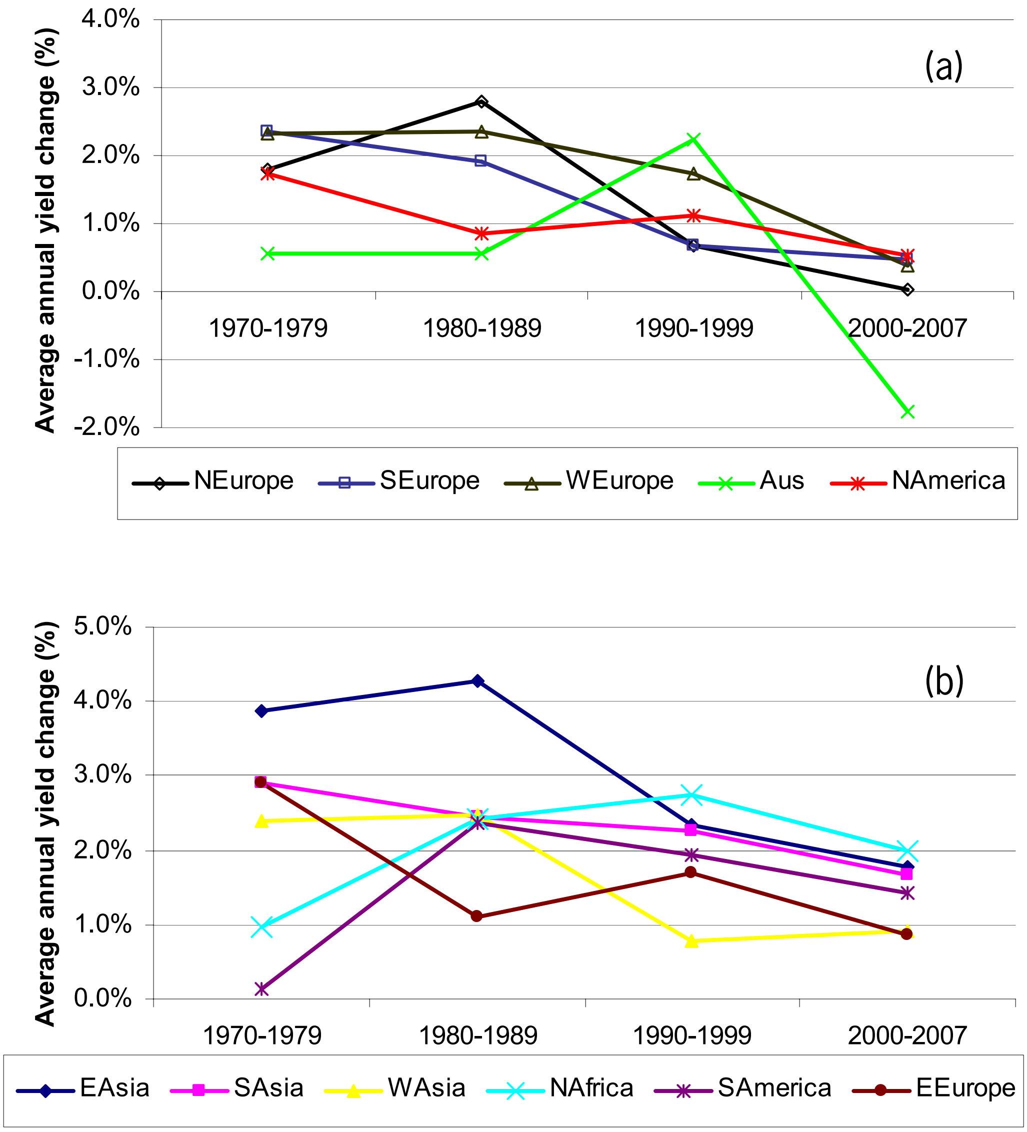


Figure 3.1 Average annual percentage change of wheat yields in advanced economies (a) and in developing and emerging economies (b) during four periods.

Table 3.3 Current wheat yields of eleven major wheat growing regions.

Region	Yield (t/ha)
Northern Europe	6.46
Western Europe	6.85
Southern Europe	3.10
Australia and New Zealand	1.32
Northern America	2.65
Eastern Asia	4.48
Southern Asia	2.51
Western Asia	2.07
Northern Africa	2.25
South America	2.44
Eastern Europe	2.36

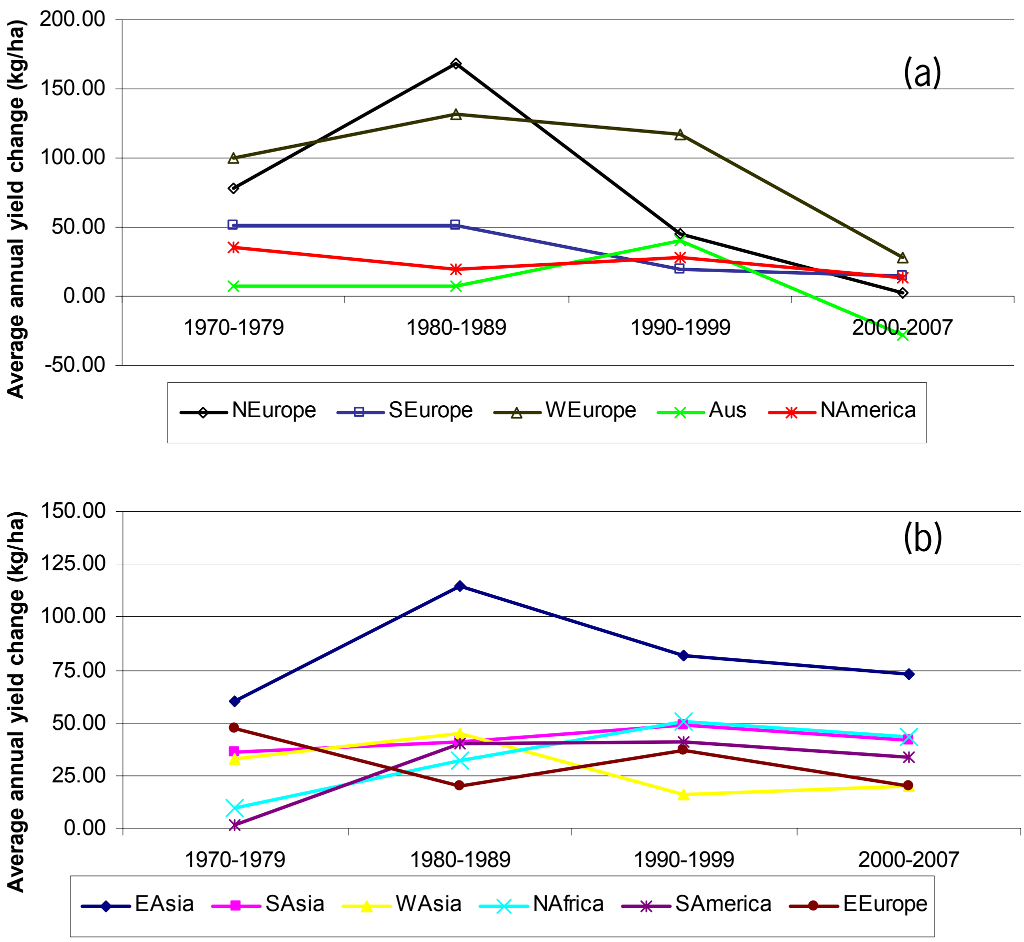


Figure 3.2 Average annual absolute change in wheat yields in advanced economies (a) and in developing and emerging economies (b) during four periods.

3.2.2 Maize

Figure 3.3 shows the average annual percentage change of maize yields for nine major maize growing regions covering about 90% of the global maize area in 2007. In Table 3.4 the average (2005-2007) maize yields of these regions are shown.

With few exceptions, maize yields still increase (in percentage) and in many regions annual growth is 2% or higher. In Southern America annual growth rates have steadily increased since 1970s and averaged more than 3.3% in the beginning of the 21st century. Only in Eastern Asia yield growth has been decreasing since the 1970's. The negative growth in Eastern Europe in the decade 1990-1999 reflects the effects of the disrupted economy but it clearly recovered in the beginning of the 21st century. Remarkable is that the yield growth in Western Africa has been consistently higher than in Eastern Africa since 1970-1979.

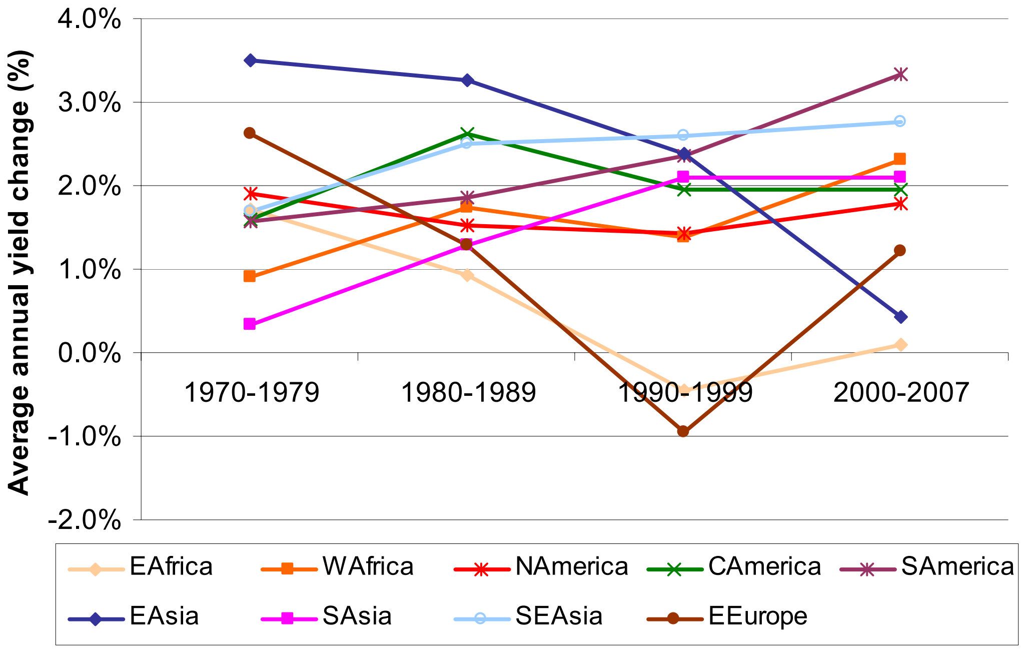


Figure 3.3 Average annual percentage change of maize yields in nine major maize growing areas during four periods.

Table 3.4 Current maize yields of nine major maize growing regions.

Region	**Yield (t/ha)**
Eastern Europe	4.16
Northern America	9.34
Central America	2.28
Southern America	3.91
Eastern Asia	5.22
South Eastern Asia	3.23
Southern Asia	2.37
Eastern Africa	1.36
Western Africa	1.62

3.2.3 Rice

Figure 3.4 shows the average annual percentage change of rice yields for four major rice growing regions covering over 90% of the global rice area in 2007. Average (2005-2007) rice yields of the regions are: 6.26 t/ha in Eastern Asia, 3.35 t/ha in Southern Asia, 3.88 t/ha in South Eastern Asia and 1.62 in Western Africa.

Average annual progress in rice yields tends to decrease in three regions; in Western Africa yield growth is even negative. The decline in yield progress is largest in Eastern Asia, which realizes the highest rice yields.

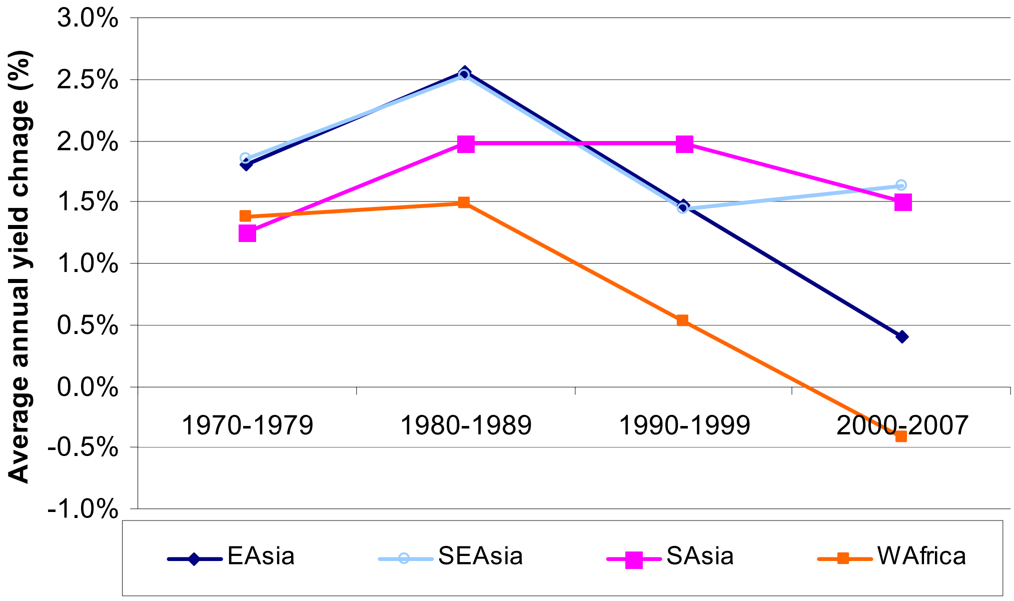


Figure 3.4 Average annual percentage change of rice yields in four major rice growing areas during four periods.

3.3 Expert-based yield gap analysis

3.3.1 Introduction

Out of the 23 experts approached with the email survey over 60% replied with suggestions on methodological issues, (grey) literature on yield gap analyses, and practical information related to the yield performance in specific cropping systems. Ideally, the expert survey would have provided quantitative information on the relative contribution of the production constraints to existing yield gaps of the different crops. However, only few experts provided such quantitative estimates. Some experts provided qualitative estimates while several other experts provided quantitative estimates of yield loss factors using different conceptualizations. On the one hand the few quantitative estimates received confirm the challenging task that was asked from the experts. On the other hand, similar efforts of peer colleagues indicate the relevancy of this study.

Although the primary goal of this survey was not fully realized, the information unlocked provides helpful insights for the identification of policies aimed to increase current crop yields around the world. In addition, it may contribute to improve future initiatives focusing on either yield gap analysis or measures to improve yields in practice. In the following sections we address the feed-back and data that were provided by the experts, and we present the information from the literature.

The information was found to be skewed towards major cereals, mainly rice, wheat and maize, which is easily explained as these crops are the most relevant food crops (Cassman, 1999), and subject of a vast majority of agronomic research efforts. The four major cropping systems in which these crops are grown represent the foundation of the human food supply system: (i) irrigated annual double- and triple-crop continuous rice systems in the tropical and subtropical lowlands of Asia - accounting for some 25% of global rice production, (ii) irrigated annual rice-wheat double-crop systems - the primary cereal production system in northern India, Pakistan, Nepal, and southern China, (iii) temperate maize-based, rain-fed cropping systems of the North American plains - contributing more than 40% of global maize supply, and (iv) the favorable rain-fed wheat systems of northwest and central Europe - accounting for more than 20% of the total global wheat supply (Cassman, 1999).

Conditions and crop yields in these systems play a major role in the analysis that will be presented, completed with observations on some industrial crops (potato, sugar cane, sugar beet) plus individual observations on other crops. But before we present the analyses, we will start with addressing methodological issues.

3.3.2 Definitions and concepts

Many of the comments and remarks that were received can be traced back to the use of different definitions and concepts. Both yield measures in the survey, i.e. current farmer and potential yield levels, were subject to debate. The impression is that few crop experts make extensively (implicit) use of the definitions as provided in the survey. For most of the others, these concepts are less obvious, their use being less common. Consequently, among those who provided feedback, the experts used different definitions and methods to estimate yield measures. This makes it worthwhile to devote some words on these issues in this section, as this may contribute to a more sound analysis, plus the development of a set of yield measures.

There are a number of measures of crop yield, defined as the weight of grain harvested per unit of land at a given (standard) moisture content (Fischer *et al.*, 2009). As our analysis includes also non-cereal crops such as potato, cassava, sugar cane, sugar beet and cotton, it may be better to refer to 'economic product' or 'main product' rather than 'grain'. For reasons of simplicity, however, we will use ´grain´ in the remainder of this report.

The definition of crop yield points at several related issues: First, production statistics, - as the main source for estimating average farm yields (see later) - , do not always distinguish yields according to the end-use of the crop (e.g. making no distinction between barley cultivated for either brewing or animal feed; starch *vs.* seed, or consumption potato, or sugarcane for biomass or canes). As farmers (and researchers) do treat such production systems differently (e.g. providing alternative management, optimizing economic rather than biological yields), this may easily result in comparing apples (e.g. brewing barley production) and oranges (e.g. feed barley production systems).

Second, the moisture content of the grain usually is not reported or standardized in statistics. Deviations may be small for most cereals, but may be much larger for other crops, thus hindering fair yield comparisons.

Third, perennial crops (sugarcane, palm oil) show significantly lower yields during early and late stages of plantation development. Including production figures from different stages thus may hamper yield comparisons (e.g. when comparing annual figures, or figures from regions which show large differences in average crop ages). Related to this is the issue whether yields of perennials are expressed per unit of harvested area or per unit of area plantation.

Fourth, many tropical regions have multiple growing seasons, each with different yield potentials. Some crops, like rice or potato, can be grown in different seasons in the tropics, showing important differences in productivity between the seasons. This effect may be aggravated if a major crop is followed by a secondary crop that harvests residual water and nutrients. The objective for this so-called relay cropping system is to optimize the use of limited resources, not yield optimization of the second crop. Statistics may further be troubled by observations of double-cropping (crops grown in two sequential seasons), often found in Asia, as yield observations sometimes cover both sequential crops (thus providing aggregated production per year).

Notwithstanding the problems and potential sources of confusion listed above, what is needed is a common denominator to express actual crop yields. Starting point here is the *average farm yield* which is defined as the average yield achieved by farmers in a defined region and period (Fischer *et al.*, 2009). Taking into account the remarks in the previous paragraph, farm yields can be estimated by using regional, national or international statistics, or through ground or satellite surveys of fields.

Many experts introduced implicitly or explicitly a yield level, which maybe best described as the *economically attainable yield* level which is defined as the optimum (i.e. profit maximizing) yield given prevalent economic conditions (prices paid/received by farmers, taxes, etc.), taking into account risks and existing institutions (Fischer *et al.*, 2009). Economically attainable yields are achieved with best management practices, controlling yield-limiting and yield-reducing factors at economical levels. In other words: the yield that a skilful farmer can realize when taking prudent account of production conditions, economics and risks. Interpretation of this concept is not without problems as it implies that economically attainable yields are driven by prevailing price levels, while these may be distorted by subsidies, taxes, poor infrastructure and institutions.

Several experts suggest that the economically attainable yield can be derived from average yield levels in regions with intensive and modern agricultural practices, well-functioning institutions, good infrastructure and minimal subsidies. Under these conditions, average farm yields tend to level out at 70-80% of the yield potential, an apparent yield ceiling. This has been observed for the intensive rice systems in China, Japan and Korea (Cassman, 1999; Cassman *et al.*, 2003; Lobell *et al.*, 2009) and wheat production in the United Kingdom (Fischer *et al.*, 2009). Experts report similar yield ceilings for other crops as well, e.g. irrigated sugarcane. The difference between potential yields and economically attainable yields can partly be understood by the notion that farm management is a function of seasonal conditions that are not known at the time of decision-making resulting in management decisions hindering the realization of the full yield potential of a crop.

Although the method to estimate economically attainable yield is most often applied in non-constrained conditions facilitating the realization of potential yield levels, the concept itself may be equally valid under water-limited production situations. In that case, the economically attainable level may be lower than 70-80% of the yield potential under such conditions. It goes beyond the scope of this study to discuss this in detail, but the associated yield range is most likely broader than under irrigated conditions given the higher uncertainty in production conditions under rain fed situations.

Table 3.5 Concepts of yield measures based on Van Ittersum and Rabbinge (1997), Fischer et al. (2009), Dobermann (pers. com.).

Yield	Definition	Estimation method
(1) Average farm yield	Average yield achieved by farmers in a defined region and period	Regional or national statistics, ground or satellite surveys of fields.
(2) Economically attainable yield	Yield achieved with best management practices implemented at economical levels of controlling yield-limiting and yield-reducing factors	70-80% of the yield potential for non-water limiting conditions
(3) Potential yield	Maximum yield with latest varieties, removing all constraints, including moisture, at generally prevailing solar radiation, temperature, and day length	Highly controlled on-station experiments, best farmers, crop models calibrated with latest varieties, well-monitored crop contests.
(4) Water-limited potential yield	Maximum yield under rain fed conditions, removing all constraints as for potential yield except for moisture.	Highly controlled on-station experiments, best farmers, crop models or crop contests.
(5) Exploitable yield gap	Difference between economically attainable yield and average farm yield	(2) – (1)
(6) Theoretical yield gap	Difference between potential yield and average farm yield	(3) – (1)

Note that (i) the difference between economically attainable yields and average farm yields indicates the exploitable yield gap under prevailing socio-economic conditions, and (ii) individual farms may realize yields that exceed economically attainable yields. The existence of an exploitable yield gap is believed necessary to maintain growth in average yields (Lobell *et al.*, 2009). Large exploitable yield gaps indicate major opportunities for research and the need for improvements in crop management, infrastructure, enabling institutions and markets. When average farmer yields begin to plateau at economically attainable yield levels and closing of the exploitable yield gap stagnates yield growth can be maintained in two ways: (i) crop breeding to increase the yield potentials (Section 3.4), and (ii) more favorable input and output prices motivating farmers to invest in technologies required to bridge the theoretical yield gap.

3.3.3 Regional classification

The used regional classification dividing the World in 11 regions raised the concern of some crop experts. One of the experts indicated that a sub-division according to the 'Mega-environments' of the International Maize and Wheat Improvement center (Anonymus, 2002), or according to climate types -temperate, Mediterranean, subtropical, tropical, semi-arid en arid – could yield more relevant information. Another expert argued that FAO classification would be most appropriate for this type of studies.

Despite the fact that the experts and the literature (provided by the experts) use different geographical divisions the used regional classification does not seem to have been the major obstacle for crop expert to provide the requested quantitative information. Yet the used regional classification posed problems in dovetailing current regional farmer yields from FAOSTAT (Section 2.2; Table 2.5).

3.3.4 Expert estimates of potential yields

See Annex II for the actual FAO yields and IMAGE potential yields. The IMAGE team is currently working on a new crop model, replacing the currently used GAEZ, which has not been updated during the last 20 years. The new model is also expected to reflect results of breeding over the last two decades and its impact on yield potentials. Experts were presented an overview of current and potential yields, the latter thus being based on figures that currently are being updated. Some experts suggested new values for potential yields (Table 3.6). The expert yields provided for maize were 80% of the water-limited yields but have been converted to 100% water-limited yields to facilitate better comparison with the IMAGE yields.

For maize and potato, the difference between the IMAGE and expert yield estimates are considerably (Table 3.6). For maize the comparison is between potential yields (IMAGE) and the water-limited yields (expert), which may be lower than potential yields in environments where rainfall is limiting production. However, especially for North America and NE Asia expert maize yields are much higher than the IMAGE estimates. According to the expert, one of the major limitations in current maize production in North America is the low plant population (due to high costs for genetically modified seeds) and uniformity of intra-row plant spacing. For NE Asia, the yield potential is higher than suggested by IMAGE because of the poor hybrids and lack of balanced crop nutrition in China.

Also the potato yield estimates of the expert are very different from those estimated by IMAGE (Table 3.6). The average potential potato yield estimated for the European Community is about 75 t/ha (De Koning and Van Diepen, 1992), which is much larger than the potential yield calculated by IMAGE. Potato yields of IMAGE also seem in the low range if we consider that the yield gap (i.e. difference FAO and IMAGE yield) is only 3% in Western Europe. Such a small yield gap is unlikely and has not been reported in the literature for any other crop. Also the potential yields of cassava and sugar beet seem low compared to current yields in many parts of Western Europe (Annex II).

The differences between the IMAGE and expert yield estimates for rice are smaller in most cases than for maize and potato (Table 3.6). The expert estimate of the rice yield potential takes into account the big difference between the dry season (9-10 t/ha) and wet season (6-8 t/ha) rice production in tropical areas. A yardstick in terms of area and use in tropical areas is 2/3 wet season + 1/3 dry (irrigated) season to arrive at a weighted yield range of 8-9.3 t/ha.

The expert estimate of the potential yield for tropical cereals in semi-arid Africa and the Middle East was considerably higher (25%) than the IMAGE estimate. The expert agreed with the IMAGE yield estimates of tropical cereals for humid Africa and South Asia.

Various experts indicated that the type of cropping system is of major influence for estimating crop yield potentials, i.e. to distinguish between rain fed and irrigated systems. Hence, this would mean that in addition to the yield gap analysis as done in this study, also differences between water-limited crop yield potentials and average farm yields for relevant cropping systems need to be included.

Table 3.6 Yields of maize, potato, rice and tropical cereal from FAO (farm yield), IMAGE (potential yield) and experts (potential yield for potato, rice, and water-limited yield for maize). Expert yields per crop based on one expert. Blank cells indicate the region-crop combinations that were not assessed (Section 2.4.1).

	Maize yield (t/ha)			**Potato yield (t/ha)**			**Rice yield (t/ha)**			**Tropical cereals (t/ha)**		
Region	FAO	IMAGE	Expert	FAO	IMAGE	Expert	FAO	IMAGE	Expert	FAO	IMAGE	Expert
Latin America, Caribbean	3.5	10.0	10.0									
North America	9.3	10.5	15.0									
Semi-arid Africa, Middle East	3.0	10.1	12.6							0.7	7.6	9.5
Humid Sub-Saharan Africa	1.6	9.7	8.7				1.6	10.8	9	1.5	8.2	8.2
Western Europe	9.0	9.6	12.0	34.6	36.9	110						
Central, Eastern Europe	1.0	9.5	11.9	14.3	39.6	90						
CIS				12.7	43.7	90						
NE Asia	5.3	6.7	10.0				6.3	7.1	9.5-10			
South Asia	2.1	11.7	10.0				3.3	9.0	9-9.5	0.9	8.7	8.7
Southeast Asia	3.2	9.8	10.0				3.9	9.9	8.5-9			
Australia, New Zealand, pacific												

3.3.5 Expert yield gap analysis

In general, the experts recognized the difficulty to explain the yield gap by five interacting production constraints, i.e. sub-optimal availability of water, nutrients, crop protection, labour/mechanisation and/or knowledge. Some indicated that it was impossible to make a distinction among these production constraints, while others indicated that the first three constraints, i.e. (i) water, (ii) nutrients and (iii) pests, weed and diseases are the true yield gap components. The other two yield gap components, i.e. (iv) mechanization and (v) knowledge have an indirect impact on yields through the three main yield gap components. Production constraints related to soil problems such as acidity, salinity and alkalinity and that can not be counterbalanced by common nutrient management were missed by one expert. One of the experts indicated at the post-harvest losses of grain, which are not part of the yield gap definition but may account 10-15% in rice, for example.

Few experts provided estimates of the relative contribution of each of the five production constraints to the yield gap, which are presented in the remainder of this section. For the yield gap analysis either IMAGE potential yields or, if available, crop expert estimates of potential yields were used.

Maize

Figure 3.5 shows the results for maize and these suggests that in the advanced economies (N-America and W&N Europe) a relatively larger part of the yield gap is explained by a sub-optimal knowledge systems compared to other areas where physical production constraints are relatively more important such as the water availability in Middle & South America.

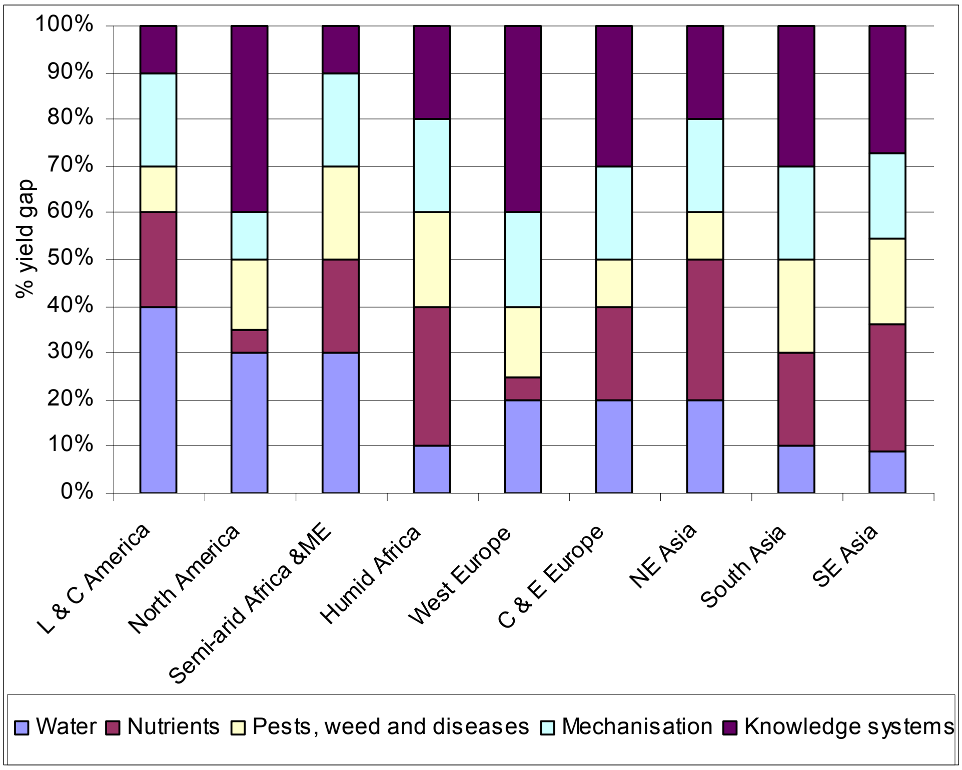


Figure 3.5 ***Maize****: Relative contribution of five production constraints, i.e. sub-optimal availability of water, nutrients, crop protection, labour/mechanisation and/or knowledge, to the gap between current and potential yields in different parts of the world.*

The absolute contribution of the five production constraints to the maize yield gap as provided by the expert provides the following information (Figure 3.6): The largest yield gap exists in Central and Eastern Europe followed by semi-arid Africa and the Middle East. Farm yields in Western Europe have almost reached the potential yield.

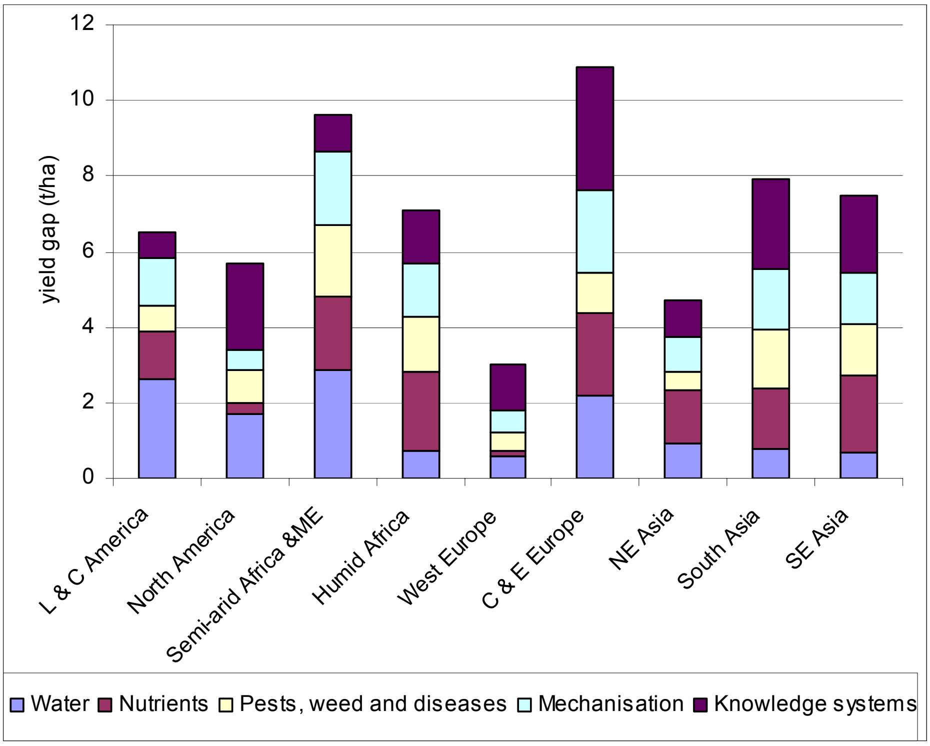


Figure 3.6 ***Maize****: Contribution of five production constraints, i.e. sub-optimal availability of water, nutrients, crop protection, labour/mechanisation and/or knowledge, to the yield gap in different parts of the World.*

Potato

Figure 3.7 shows that the yield gap for Western Europe according to the expert can be completely explained by three constraints, pest, weed and disease control, nutrient availability and especially, water availability. In the other two regions, Central and Eastern Europe and the CIS countries, mechanization and knowledge play a role, yet a minor one. The absolute contribution of the five production constraints to the potato yield gap provided by the expert shows a similar tendency and is therefore not shown. See Table 3.6 for the yields used in the yield gap analysis.

Sugar beet

Sugar beet is only a major crop in Western Europe. The average actual sugar beet yield is 63.4 t/ha and the potential yield is estimated at 80 t/ha by IMAGE. The expert estimate of the relative importance of the five production constraints indicates the importance of the knowledge system to close the yield gap (Figure 3.8), i.e. timing of operations, crop monitoring and skills. In fact, the importance of the knowledge system is larger as indicated in Figure 3.8 because the factor mechanization in this case refers to a lack of proper use of machinery for tillage, seeding and harvesting (due to a lack of knowledge). Water and nutrients are considerably less important for closing the yield gap than in other crops maybe due to strong extension support of the sugar industry (nutrients) while water-limitations are only important in a few West European countries.

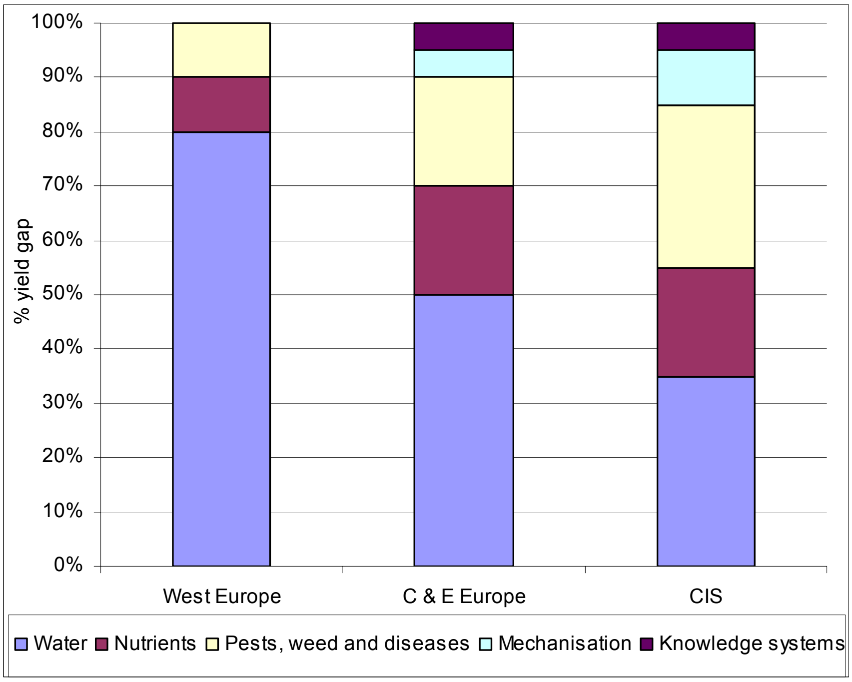


Figure 3.7 ***Potato****: Relative contribution of five production constraints, i.e. sub-optimal availability of water, nutrients, crop protection, labour/mechanisation and/or knowledge, to the yield gap in different parts of the world.*

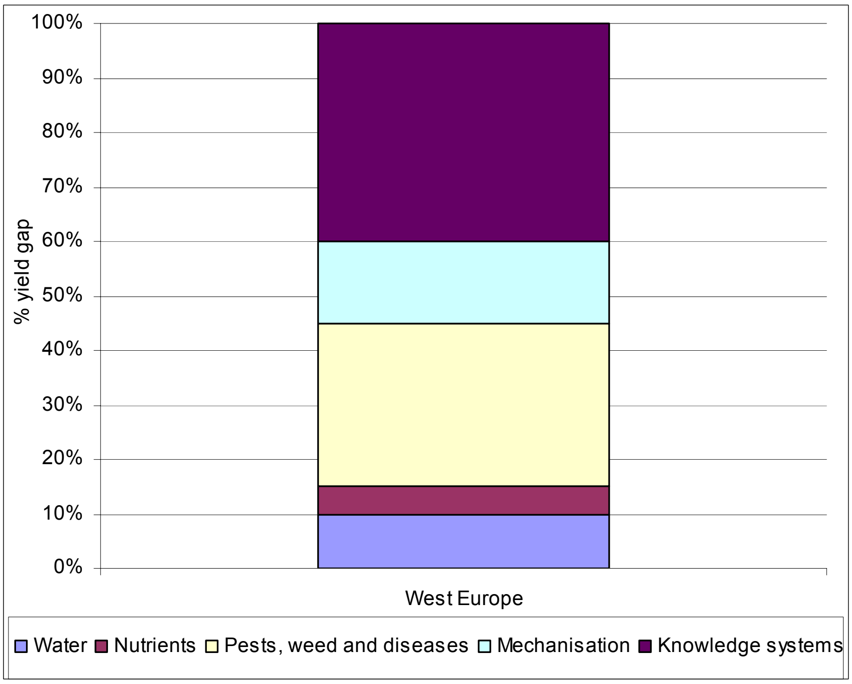


Figure 3.8 ***Sugar beet:*** *Relative contribution of five production constraints, i.e. sub-optimal availability of water, nutrients, crop protection, labor/mechanisation and/or knowledge, to the yield gap in Western Europe.*

Cassava

Cassava is important in two regions, i.e. humid Sub-Saharan Africa and South East Asia. Current yield levels are 9.5 and 17 t/ha, respectively, while IMAGE estimates of the potential yields in both regions are 39.2 and 33.9 t/ha, respectively (Annex II). Figure 3.9 shows that the contribution of production constraints to the yield gap in both regions is similar according to the crop expert. Remarkably is the large share (30%) of mechanization/labor in the yield gap, which is larger than in other crops and may be related to the time-consuming manual planting and harvesting in humid Sub-Saharan Africa and South East Asia. Also striking is the relatively small share of knowledge in explaining the yield gap.

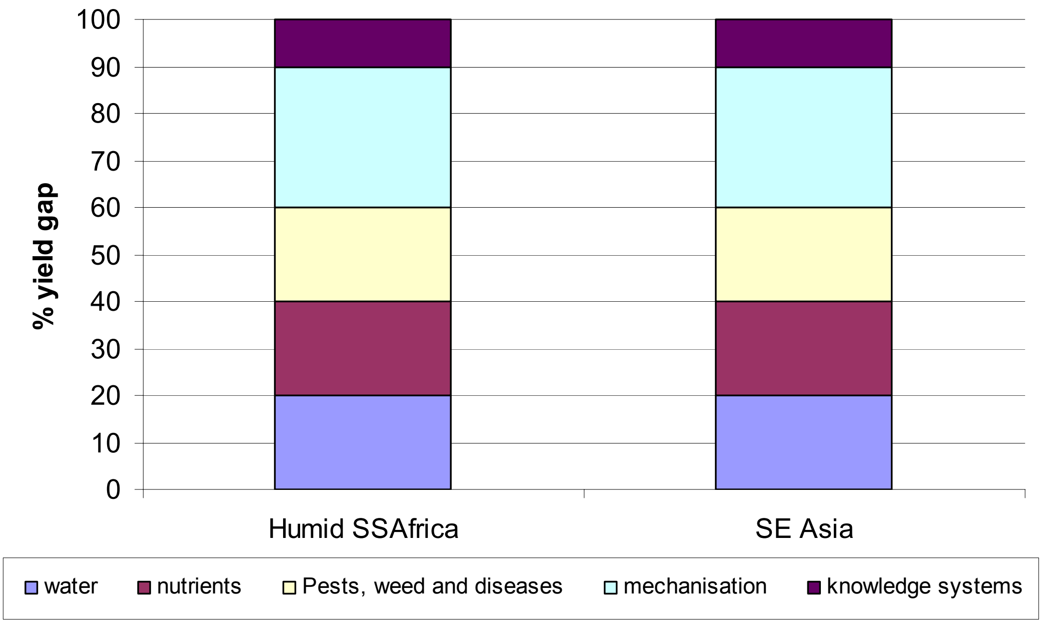


Figure 3.9 ***Cassava:*** *Relative contribution of five production constraints, i.e. sub-optimal availability of water, nutrients, crop protection, labor/mechanisation and/or knowledge, to the yield gap of cassava in different parts of the world.*

Tropical cereals

Tropical cereals, mainly millet and sorghum, are important in two regions of Africa and in SE Asia. Current yield levels are low in these regions and do not exceed 1.5 t/ha, while the expert estimate of the potential yields in these regions varies between are 8.2 and 9.5 t/ha (Table 3.6). Figure 3.10 shows that water is the most important constraint in semi-arid Africa, and pests and diseases in humid Africa according to the expert. In SE Asia the knowledge system is considered the most important production constraint for increasing current yield levels.

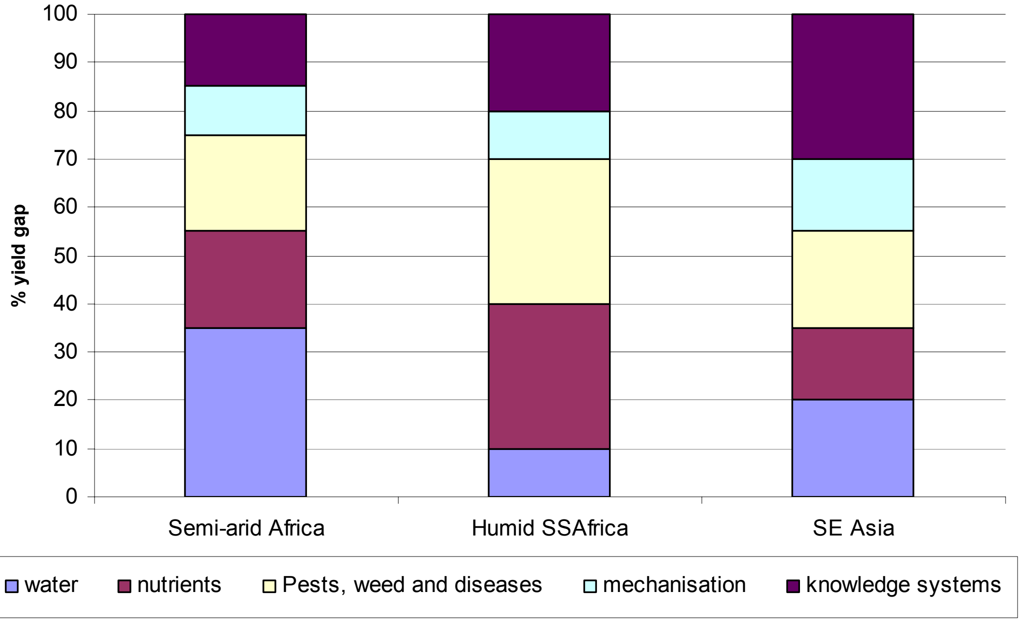


Figure 3.10 ***Tropical cereals:*** *Relative contribution of five production constraints, i.e. sub-optimal availability of water, nutrients, crop protection, labor/mechanisation and/or knowledge, to the yield gap in different parts of the world.*

3.4 Yield losses estimated in other studies

3.4.1 Losses due to weeds, pests and diseases

While the number of studies offering an integrated yield gap analysis is scarce, some studies offer data on a limited number of yield reducing factors. A good example of the latter is given by Oerke *et al.* (1999), who provide an overview of losses in major crops due to pests, weeds and diseases (biotic factors). An important difference between Oerke *et al.* (1999) and our study is the fact that the former focuses on actual yield losses while we include all losses from the potential yield level. Another difference, - that is the definition of regions used in the analysis -, has been overcome by recalculating the results of Oerke *et al.* (1999) for regions used in our study. We compare results provided by Oerke *et al.* (1999) by those given by the crop expert in our study for maize and potato.

Maize

A comparison of biotic yield losses for maize is presented in Figure 3.11. Highest losses reported by Oerke *et al.* (1999) are in C&E Europe and by the experts in semi-arid Africa. In many cases, estimations by Oerke *et al.* (1999) exceed those given by the experts. This is especially the case for major maize regions of North America and North East Asia. In semi-arid Africa and South Asia expert estimates of yield losses are higher.

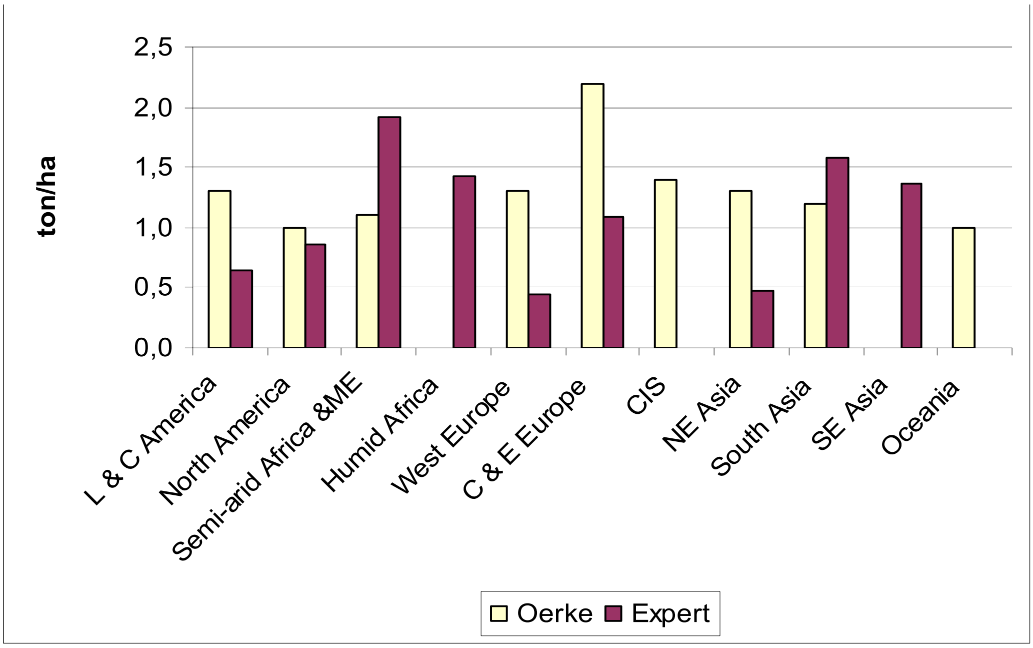


Figure 3.11 Yield losses due to pests, weeds and diseases as estimated by Oerke et al. (1999) compared to losses reported by crop expert for maize.

Potato

Results for potato are shown in Figure 3.12. Highest expert losses are estimated for CIS, while the loss estimate of Oerke *et al.* (1999) is more or less similar across the three major potato producing regions. Calculations by Oerke *et al.* (1999) exceed those of the expert slightly in West Europe, but not in the other regions. Largest difference is observed in CIS, i.e. the expert estimate being more than double the figure reported by Oerke *et al.* (1999).

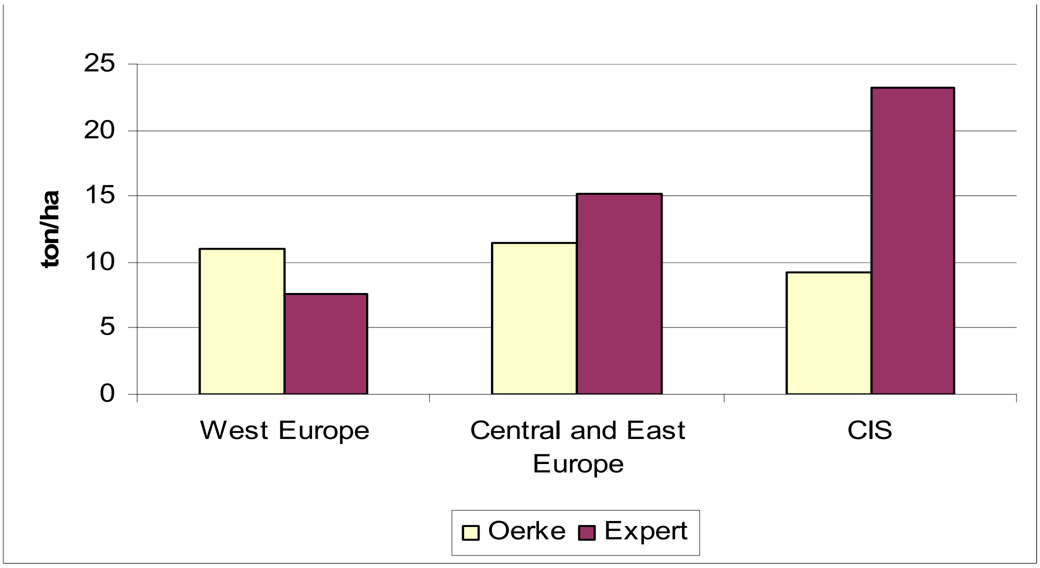


Figure 3.12 Yield losses due to pests, weeds and diseases as estimated by Oerke et al. (1999) compared to losses reported by crop expert for potato.

Discussion
Yield losses due to pests, weeds and diseases reported by experts were compared to figures from the literature (Oerke *et al.*, 1999). In many cases, loss figures by Oerke exceed those estimated by the experts. This is remarkable, as Oerke *et al.* report losses from attainable yields while experts refer to potential yields, one would expect losses from experts being higher. Relatively low estimates by experts may be explained by the fact that they also consider losses due to other factors. Losses due to shortages of e.g. water and nutrients tend to be considered as dominating, which may lead to a relatively downgrading of yield losses due to biotic factors. Another explanation may be that current yield losses due to pests, weeds and diseases have diminished in comparison to the period referred to by Oerke *et al.* (1999). This may be the case in intensively cultivated regions (e.g. maize in North America and potato in West Europe).

3.4.2 Generation Challenge Program

There are not a large number of studies that attempt to quantify production constraints explaining yield gaps in a comprehensive way. One of the most striking exceptions is a study executed in the framework of the Generation Challenge Program (GCP; http://www.generationcp.org/) of the CGIAR (Waddington *et al.*, 2009). In this study, production constraints and yield losses were analyzed for wheat, rice, sorghum, cowpea, chickpea and cassava in Sub-Saharan Africa, South Asia and East Asia. Focus is explicitly on smallholder farming systems, selecting those with highest prevailing poverty. Surveys have been conducted with over 600 experts of different backgrounds and experience, feeding preliminary results back into small focus groups using the so-called Delphi method.

GCP identifies a great number of production constraints which can be re-grouped into abiotic, biotic, management and socio-economic categories. These show many similarities to the ones used in our study, the latter category being however of a different character. Abiotic factors include shortages of water and nutrients, biotic factors refer to pests, weeds and diseases, management to issues of labor and mechanization.

Detailed results for the GCP study have yet to be published, but could be used to undertake a more detailed comparison with our results once more details of the GCP study come available.

3.5 Yield progress by breeding

The effect of breeding on the progress in crop yield potentials is difficult to distinguish from the effect of technological progress (i.e. improved agronomy). Often, the observed progress in yields is based on the exploitation of positive interactions between genotype and management for yield increase. For example, the yield benefit of semi-dwarf wheat and rice varieties is at high nitrogen input levels considerably higher than that of the older varieties they replaced.

One way to estimate the progress in yield potential due to breeding is to compare historic sets of varieties grown under high inputs and pests and diseases are effectively controlled. Progress can be calculated by plotting yields against the year of release of each variety (Fischer and Edmeades, 2009). Although the comparison of historic sets of varieties allows excluding yield gains due to agronomic innovation alone, the progress in potential yield is achieved under advanced agronomy and thus includes the genetic (breeding) gains plus the genotype by management interaction gains which are often significant (Evans and Fischer, 1999). Since newly released varieties are selected and adapted to withstand contemporary conditions older varieties are often not. Hence, even with the best possible management practices to minimize the confounding interaction effects of selection under different environmental conditions, it is not always possible to fully protect and optimize growing conditions for older varieties in comparative trials (Cassman *et al.*, 2003). With this possible flaw in mind, Fischer *et al.* (2009) estimate the annual progress in potential yields of rice and wheat both at about 0.5% on the basis of a number of case studies in different regions of the world. Because of the uncertainty in the estimation of potential yields of hybrid maize varieties, the potential yield progress of maize is less certain but it is estimated higher, around 1% per year. One of the reasons for the greater progress in the yield potential of maize is that rice and wheat breeders give more attention to grain quality traits and disease resistance than in the case of maize (Fischer *et al.*, 2009).

Hybrid vigor has been heavily exploited in maize and rice breeding. Depending on the literature source, hybrid rice provides a 7-10% (Duvick and Cassman, 1999), 9% (Peng *et al.* 1999) to 10-20% (Dobermann, pers. comm.) yield advantage compared with the best inbred varieties. The recently developed "Super" rice hybrid varieties in China provide a 8-15% yield boost compared to available rice hybrids (Peng *et al.*, 2008). One major obstacle in the spread of current hybrid rice varieties is that their consumption quality is less preferred in many parts of Asia, reducing the rate of adoption. At the moment, hybrid rice is grown at about 21 million ha (out of 160 Mha total rice harvest area), and 16 Mha of that is in China. If adoption of hybrid rice varieties continues it is expected that the area with hybrids will rise to at least 30 Mha within few years. Hence, in theory, average yield potential will be increasing slightly in areas where hybrids will be adopted. Development of hybrid wheat also may deliver an increase in yield potential, but it remains in the experimental phase because of high seed production costs (Cassman, 1999). More successful has been the introduction of hybrid maize varieties and although there is some controversy about the progress in yield potential of maize hybrids (see above), they do respond better to fertilizers and higher plant densities resulting in higher average farm yields (Duvick and Cassman, 1999).

In short, switching to hybrids may provide a one-time boost to the yield potential in many crops. Thereafter, further increases in yield potential depend on an increase in canopy photosynthesis per unit of intercepted light or a decrease in the metabolic costs of synthesis and maintenance of carbohydrates, proteins, and lipids. There is little evidence, however, that plant physiologists or breeders have been successful at increasing the assimilatory or metabolic efficiencies of the major cereal crops (Evans, 1993). The processes governing radiation use efficiency, a parameter that integrates both photosynthetic capacity and metabolic costs, are conservative and therefore offer little opportunity for improvement through genetic manipulation (Sinclair, 1993). However, the International Rice Research Institute has an ambitious project to genetically engineer the more efficient C_4 pathway into C_3 rice to improve CO_2 supply to Rubisco. Latter is the central photosynthetic enzyme that limits the maximum photosynthetic rate in C_3 crops due to a relatively inefficient capturing of CO_2. If the genetically engineering of C_3 into C_4 rice is successful, current rice yields of 9 t/ha could increase by 50% (Sheehy *et al.* 2007). However, in the medium term these engineering activities are not expected to bear fruits because of the complexity of the engineering tasks (Fischer *et al.*, 2009).

Most experts are skeptic about the contribution of genetically engineering to increasing the maximum potential yields of crops. Most efforts in this field aim at improving stress resistance traits such as herbicide resistance, insect resistance and drought tolerance. Obviously, genetically modified (GM) drought tolerant crops may increase *water-limited* yields in drier areas and other stress resistant improvements reduce the needs for inputs (input-saving) allowing a more rapid closing of the yield gap between potential yields and farm yields, but they are not enhancing the yield *potentials* of crops. Part of the rapid progress in maize farm yields in the US corn belt is associated with the better weed and insect control made possible by the introduction of GM maize hybrids (Fischer and Edmeades, 2009). Since the introduction of GM maize in the US corn belt in 1996, 90% of the maize area is now sown with GM maize which has contributed to a spectacular annual growth of 2% in farmer yields in Iowa (Fischer *et al.*, 2009).

In short, most experts agree that GM crops result in higher farmer yields in the short term and that they play an important role in closing the exploitable yield gap by reducing losses, for example, due to pests and diseases. However, experts are less optimistic that GM crops may increase yield potentials of crops.

3.6 Yield projections

This section analyses the collected information on yield levels (Section 3.3.4), yield gaps (Section 3.3.5) and current yield progress due to breeding (Section 3.5) in relation to the yield projections of FAO (Bruinsma, 2003) which are used by IMAGE. The analysis is performed for wheat, maize and rice in the relevant regions (Table 2.6). Since the IMAGE regions differ from ours (Table 2.4), Table 3.7 provides the FAO yield growth data used for the different regions and crops. In most cases, our regions comprise several IMAGE regions. In general, we have used in the analysis those IMAGE regions with the highest yield growth rates. This allows analyzing the effect of the highest projected growth for a specific crop-region.

Table 3.7 FAO yield growth data used in the different regions. Blank cells indicate that the region-crop combination is not assessed.

Region	**IMAGE region**	**Yield projections (% per year)**		
		Wheat	Maize	Rice
1. Central and south America, Caribbean	Rest Central America (for maize and wheat); Brazil (for rice)	1.37	1.85	1.35
2. North America	USA	0.33	0.89	
3. Semi-arid areas of West Asia and Africa	East Africa	1.32	1.44	
4. Humid Sub-Saharan Africa	Southern Africa		1.24	2.18
5. Western Europe	OECD Europe	0.47	0.36	
6. Central and Eastern Europe	Turkey	0.88	1.15	
7. CIS	Asia Stan	1.11		
8. Northeast Asia	Korea	0.69	1.41	0.57
9. South Asia	India	1.33	1.49	1.23
10. Southeast Asia	South East Asia		1.27	0.96
11. Australia, New Zealand and Pacific	Oceania	1.02		

Wheat

Figure 3.13 shows the current wheat yields, potential yields as estimated by IMAGE, growth in the yield potential of wheat based on current progress in breeding (0.5% per year, Section 3.4) and the yield projection according to FAO for the years 2000, 2015, 2030 and 2050 based on the annual growth rates shown in Table 3.7. Large differences exist in actual yields and yield gaps among regions.

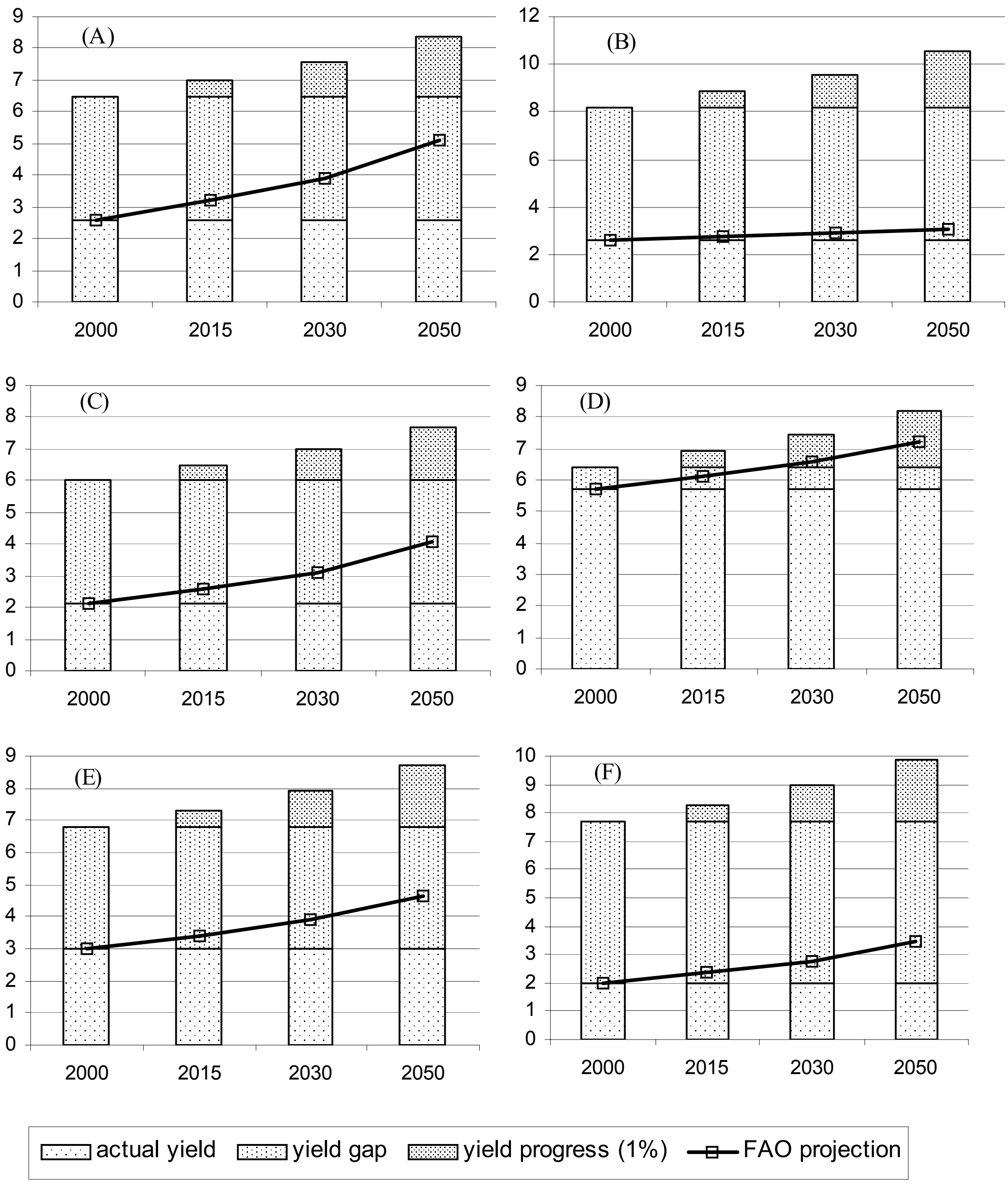
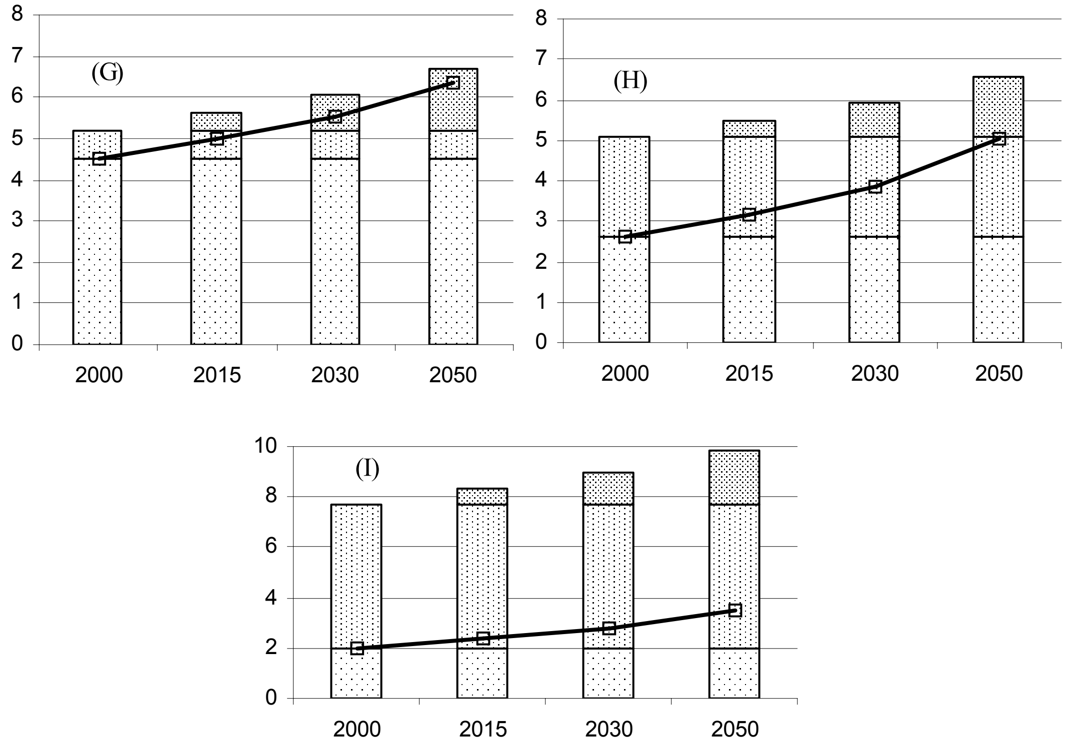


Figure 3.13 Current yield, expert potential yield (in t/ha on X-axis), progress in yield potential due to breeding (0.5% per year) and the yield projection according to FAO for the years 2000, 2015, 2030 and 2050 for wheat in Central and South America (A), North America (B), Semi-arid Africa (C), West Europe (D), Central Eastern Europe (E), CIS (F), North East Asia (G), South Asia (H), Australia, New Zealand, pacific (I). *Continued on next page.*



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The FAO projection based on an annual growth of 0.47% closes the current yield gap for wheat in Western Europe in the year 2030 (Figure 3.13D). In 2050, the FAO projection would be clearly higher than the simulated potential yield of IMAGE, but still below the higher yield potential provided that the current progress in yield potential as a result of breeding efforts is maintained. It is noted that the IMAGE estimate of the potential wheat yield for OECD Europe is very low (6.4 t/ha), which explains the relatively small current yield gap (only 1.07 t/ha). De Koning and Van Diepen (1992) simulated regional potential wheat yields for 12 countries of the European Union and their lowest potential yield estimate was 7.5 t/ha for a region in Greece. In their study the majority of potential wheat yields were around 10 t/ha. This is still low compared to the theoretical estimate of the yield potential for wheat in the UK which is 19 t/ha (Sylvester-Bradley *et al.*, 2005). A similar overshooting of the potential wheat yield happens in Northeast Asia in 2030 (Figure 3.13G). Also in this case the IMAGE estimate of the potential wheat yield (5.2 t/ha) seems in the low range of what may be feasible. Dingrong Wu *et al.* (2006) estimated average potential wheat yields for the North China Plain at more than 8 t/ha.

The FAO projections for wheat yields in North America, CIS and Australia (Figure 3.13B, F and I) show that these are much lower than what possibly could be gained by closing current yield gaps. In contrast with most wheat growing areas in the Western Europe, many wheat growing areas in the North America, CIS and Australia face water shortages, which limit current wheat yields. Since, it is unlikely that wheat can be irrigated in a sustainable way in the future, potential yield levels will remain out of reach also on the long-term as illustrated by the FAO projection. GM drought resistant wheat varieties may help to overcome water-limitations and may be instrumental in further closing the yield gap.

Maize

Figure 3.14 shows current maize yields, expert potential yield estimates, growth in yield potential based on the current progress in breeding (1% per year) and the yield projection according to FAO for the years 2000, 2015, 2030 and 2050. Regions differ considerably in actual yields and yield gap.

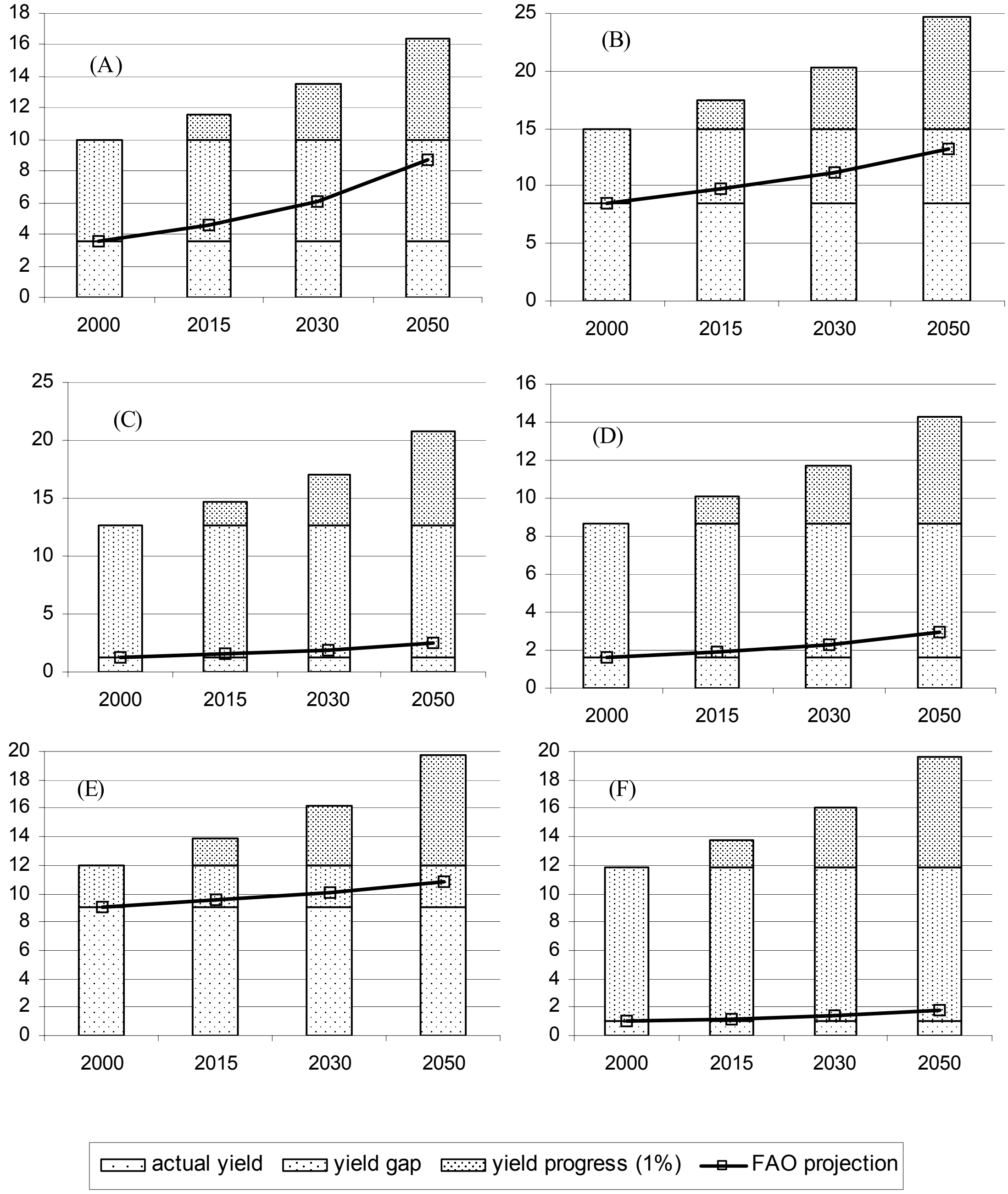
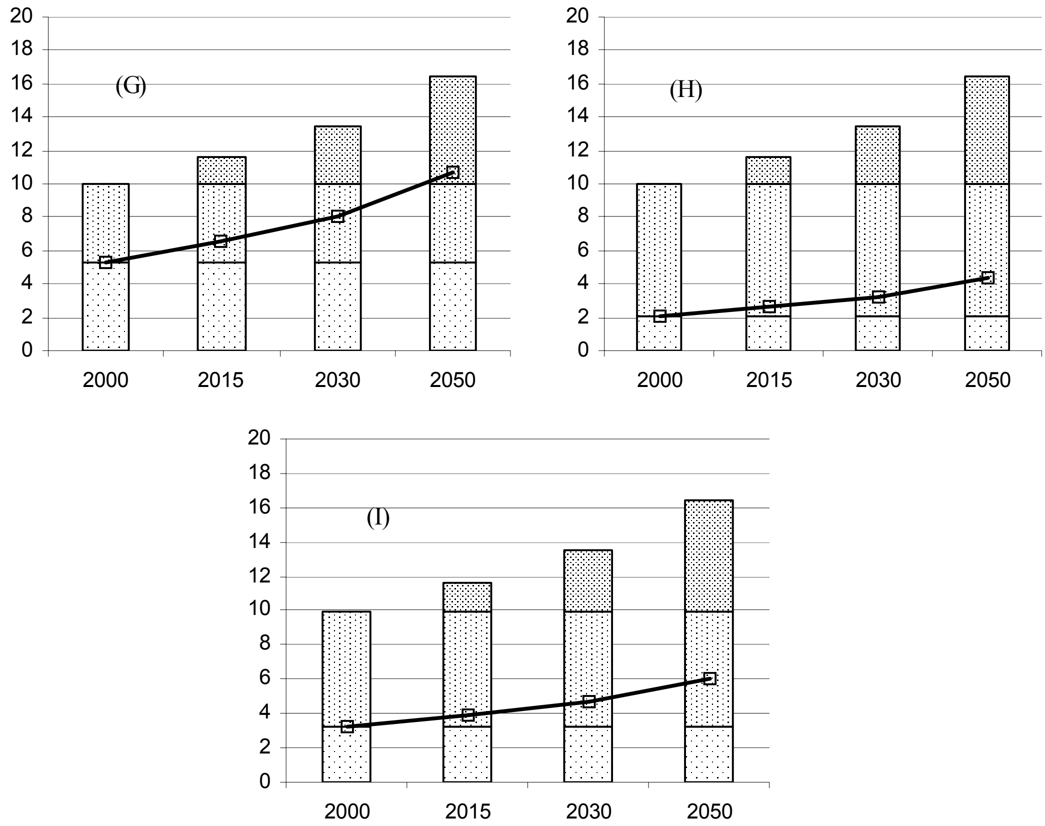


Figure 3.14 Current yield, expert potential yields (in t/ha on X-axis), progress in yield potential due to breeding (1% per year) and the yield projection according to FAO for the years 2000, 2015, 2030 and 2050 for maize in Central and South America (A), North America (B), Semi-arid Africa (C), Humid Sub Saharan Africa (D), Western Europe (E), Central Eastern Europe (F), North East Asia (G), South Asia (H), Australia, New Zealand, pacific (I). *Continued on next page.*



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The FAO projection for North America, based on an annual yield increase of 0.89%, nearly closes the current yield gap in the year 2050 as it approaches the expert estimate of the potential yield (15 t/ha). An additional progress in yield potential of 10 t/ha is possible assuming that the current growth in yield potential due to breeding (1%) can be maintained till 2050. At that point the theoretical radiation-limited maximum for maize yields in the US will be reached, which has been estimated at approximately 25 t/ha (Tollenaar and Lee, 2002). Leading maize seed company Monsanto (monsanto.mediaroom.com) aims at increasing US farm maize yields to 20 t/ha by the year 2030 (Edgerton, 2009), which corresponds well with the additional yield gain assumed by breeding efforts (Figure 3.14B).

Especially in Eastern Africa, humid Sub Saharan Africa and Central and Eastern Europe FAO yield projections are much lower than what possibly could be gained by closing current yield. In fact, the assumed progress in yield potential due to breeding increases the yield gap as the associated yield increases in absolute terms are larger than the absolute yield increase of the FAO projections.

The FAO projection overshoots the expert yield estimate in North Eastern Asia in the year 2050. Potential maize yields for the North China Plain in Eastern Asia have been estimated at approximately 10 t/ha (Wu *et al.*, 2008) corresponding well with this expert value.

Rice

Figure 3.15 shows current rice yields, expert potential yields, progress in yield potential based on current progress in breeding (0.5% per year, Section 3.4) and the yield projection according to FAO for the years 2000, 2015, 2030 and 2050.

In none of the regions the FAO growth projection overshoots the expert estimate of the potential yield. The FAO projected growth in Southeast Asia closes the current yield gap for about 50% in the year 2050. However, if we assume that the current progress in yield potential due to breeding can be maintained at 0.5% per year till 2050, then the yield gap remains almost the same (5.3 t/ha) in 2050.

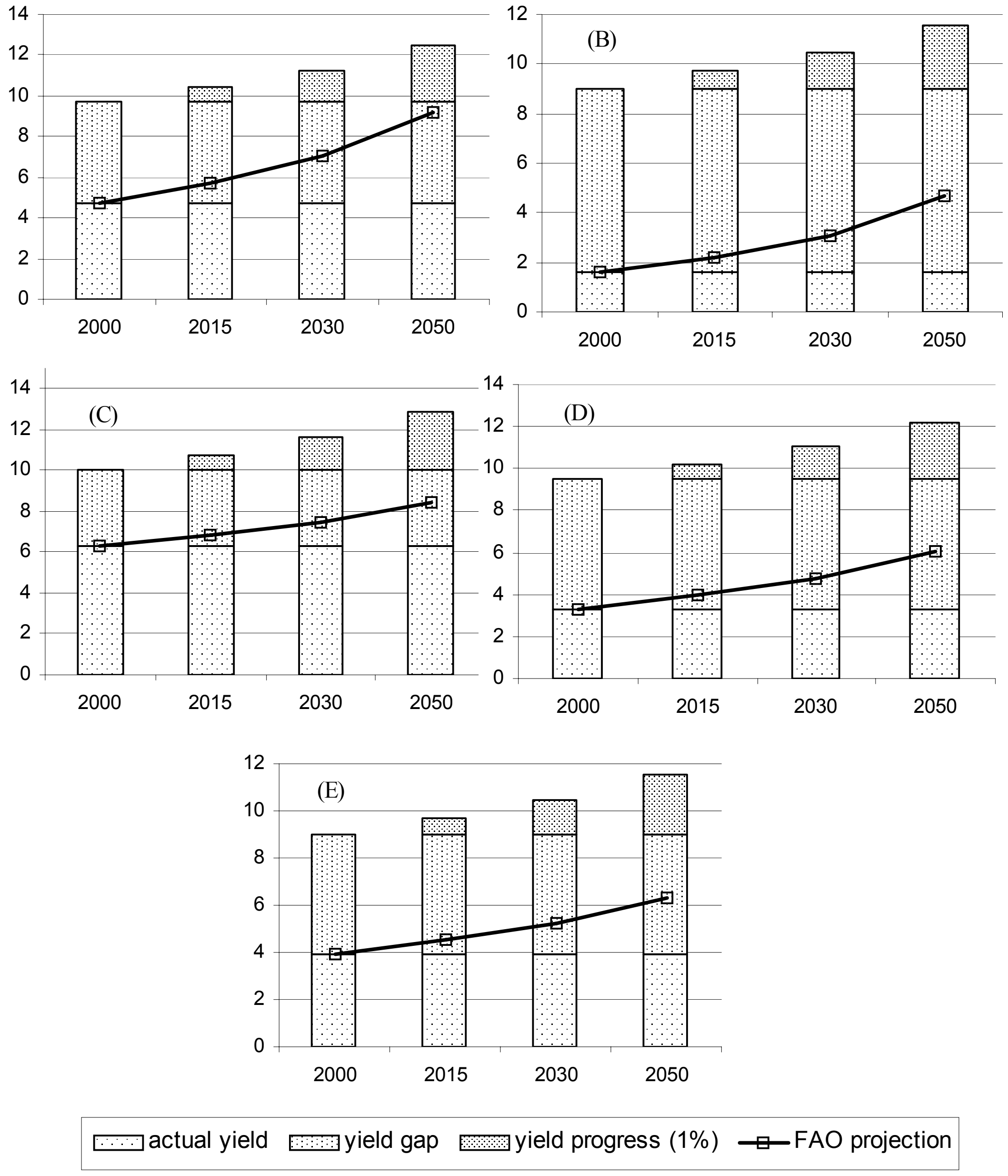

Figure 3.15 Current yield, expert potential yield (in t/ha on X-axis), progress in yield potential due to breeding (0.5% per year) and the yield projection according to FAO for the years 2000, 2015, 2030 and 2050 for rice in Middle and South America (A), Humid Sub Saharan Africa (B), Northeast Asia (C), South Asia (D) and Southeast Asia (E).

4 Discussion and conclusions

4.1 Yield growth

Yield growth has been the dominant source of recent production increases in most crops, except for soy bean and oil palm. The latter two crops also showed a strong increase in production area during the last two decades. The combined effect of the stagnating or even negative growth in the area of major cereals (e.g. wheat) and in production per unit of area in relation to the increasing global food demand is alarming and seems to confirm the trend of decreasing global cereal stocks during the last decade.

Though an analysis of changes in yield and crop areas at global scale is useful, it hides a considerable heterogeneity in yield performance among regions. The productivity analysis of wheat, maize and rice in the major cereal producing regions of the world showed that recent yield progress in wheat is between 0 and 1% per year in advanced economies, and somewhat higher between 1 and 2% in developing and emerging economies. Recent progress in maize yields is much higher than in wheat yields and varies in many regions between 2 and 3%, with an impressive 3.3% in Southern America as outlier. Progress in rice yields is mixed, in high productive Eastern Asia yields increase now with less than 0.5% per year, while in South Eastern Asia and South Asia annual increments of 1.5% or higher are still realized. The analysis indicates that growth rates of major wheat and rice growing regions in both percentage and absolute terms are declining. Growth rates of maize are still high in most regions but a major part of the maize production is used for livestock and biofuel production and not for direct consumptive purposes.

4.2 Yield levels

Some experts commented on the existing potential yield estimates by the IMAGE model provided in the survey (Annex II). There may be various reasons why experts disagree with the yield estimates as provided and it goes beyond this report to address these in detail. In general, expert estimates were higher than IMAGE values for potential yields. This reflects the fact that the IMAGE crop model has not been updated during the last 20 yields, while breeding has increased the yield potential of many crops. Especially the potential yield level of the root and tuber crops (consisting of potato, cassava and sugar beet) seems to be underestimated in IMAGE. But also for maize yield water-limited estimates of the experts were in some cases considerably higher than those from IMAGE.

4.3 Yield gap analysis

The term yield gap is widely used in the literature, but its components are not well-defined, i.e. the difference between some measure of yield potential and the actual observed yield (Lobell *et al.*, 2009). Most attempts to define both components of the yield gap appear to be incomplete and inconsistent, which seems to be related to the difficulty to measure and compare yield potentials and actual yields consistently under a range of environmental conditions (Lobell *et al.*, 2009).

The yield gap analysis seems to suggest that in more advanced economies, where crop levels approach economically attainable yield levels deficiencies in knowledge systems become more important compared to abiotic (water and nutrients) and biotic (weed, pests and diseases) constraints. Biotic and abiotic constraints become more important in situations characterized by large yield gaps, suggesting that considerable yield gains are possible by improving access to, and availability of water, nutrients and crop protection agents. There is one clear exception on this rule in this study, with water being a major constraint for potato yields in Western Europe. It is unclear whether this is an expert/methodological bias or indicates at a crop-specific exception.

Although almost 60% of the contacted crop experts replied somehow, few experts were able to provide quantitative estimates of the contribution of the five production constraints to the existing yield gap. Consequently, feedback generally was restricted to one expert per crop, which confirms the challenging task that was asked from the experts. It must be stressed, however, that there is a lot of interest in this kind of analysis. Various research groups (e.g. IRRI, Generation Challenge Program of the Consultative Group on International Agricultural Research) are currently conducting yield gap analyses, some of them using similar type of expert panels as used in this study (e.g. Waddington *et al.*, 2009).

4.4 Yield projections

Given the uncertainty in yield levels (Section 4.2), FAO yield growth projections were modest in most of the analyzed cases, i.e. they are generally insufficient to close the current yield gap by the year 2050. Assuming that the current progress in yield potential due to breeding can be maintained, various yield gaps even appear to increase over time. This would mean that the exploitable yield gap remains large, which is deemed necessary to maintain growth in average farm yields (Lobell *et al.*, 2009). However, it is uncertain how climate change will affect yield levels over this period. Climate change in the medium projection of the Intergovernmental Panel on Climate Change is not expected to have a significant effect on global crop yields by 2050 (IPCC, 2007). Most yields in some regions (mostly temperate) will be counterbalanced by the yield losses in other regions (mostly tropical). However, this implies that regional differences may occur. Progress in current yields is partly explained by an increase in global CO_2 which for C3 crops like wheat and rice is estimated to add 0.3% per year to the average farm yields (Tubiello *et al.*, 2007).

4.5 Concluding remarks

Production constraints as addressed in the yield gap analysis should be overcome to achieve progress in farm yields and to exploit the synergy between genotype, environment and management. The majority of the work on yield gap analysis has been carried out for wheat, maize and rice, and also the response received from experts was skewed. This is understandable in the light of the importance of wheat, maize and rice in the current global consumption system, but diversification of agricultural production is needed to satisfy the demand for multiple crop uses for food as well as feed and fuel.

This study provides an overview of yield trends of major food and industrial crops in the world. It defines actual yield gaps, contributes to the knowledge base on yield measures, and assesses the relevance of production constraints, both technical as well as non-technical. Prominent crop experts have provided their insights and shared their knowledge and data. The study especially reveals the difficulty to measure and compare yield potentials and actual yields consistently under a range of environmental conditions, and it shows the difficulty to disentangle interacting production constraints.

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Annex 1 Example of expert survey on the yield gap of maize

Introduction

Recent developments in agricultural production (impacts of climate change, increased demand for animal proteins and biofuel feedstocks, fluctuations in commodity prices) lead to a need for balanced, quantified analysis of production trends and potentials. Global models like the General Trade Analysis Project (GTAP) and the Integrated Model to Assess the Global Environment (IMAGE) that are used for such assessment require estimations of current and potential production for major crops in different areas of the world. These estimations are generally based on FAO production statistics and crop modelling exercises estimating potential yields. Results of the modelling exercises are generally described in methodological papers published and discussed in scientific fora. Relatively little attention is given to the factors explaining the yield gap between potential and actual yields. A better insight in the gap is a crucial source of information for those that want to define, assess or evaluate measures aimed at stimulating agricultural production and rural development or combating malnutrition and hunger.

The objective of this survey is to quantify factors that contribute to the current yield gap, i.e. the difference between current FAO yields (average of the years 2005-2007) and potential yields as determined by the IMAGE model. This will be done for selected combinations of crops and regions. The potential yield is defined as the yield of a crop cultivar grown in an environment to which it is adapted, with nutrients and water non-limiting and pests and diseases effectively controlled.

We identify five factors that may contribute to the yield gap:

1. **Water availability**: The availability of water during (part of) the growing season and limiting current production. Yield losses can be overcome by the supply of irrigation water.
2. **Nutrient availability**: The availability of nutrients during (part of) the growing season and limiting current production. Yield losses can be overcome by the supply of nutrients in the form of and organic and inorganic fertilizers.
3. **Inadequate crop protection**: Reductions in crop yields due to inadequate control of weeds, pests and diseases. Yield losses can be avoided by application of crop protection methods including the use of biocides, phytosanitary methods and crop rotations.
4. **Inadequate application of mechanization and/or labour:** Availability of and access to mechanization and/or labour may cause yield losses. This holds especially for non-timely or ineffective execution of time-sensitive cropping operations, such as sowing or planting. Limited availability of - or access to - mechanization and/or labour may in these cases result in delayed sowing/planting, forcing the crop to grow under less favourable conditions.
5. **Ineffective knowledge systems**: Refers to insufficient knowledge resulting in untimely or inadequate crop management. Examples are many, e.g. insufficient knowledge on crop nutrient requirements, inadequate insight in soil erosion prevention options, or crop protection management. All may possibly contribute to yield reduction.

Below, you will find an overview of actual and potential yields for a limited number of crops in their most relevant regions. Further, we provide an indicative estimation of the contribution of each of the abovementioned yield reducing factors. We are looking for feedback by specialists, both in the field as working on theoretical crop production.

Obviously, interactions may be expected between individual factors, for example water and nutrients. If you are aware of estimations of interactions, we would certainly like to be informed. Alternatively, if you feel like providing an estimation of interactions, this would be welcomed.

INSTRUCTIONS:
The table below provides the current and potential yields in different regions, and for your convenience, our estimates of the contribution of the different production factors to the current yield gap. A description of the regions is provided in the Annex.
1. Change the values if necessary in this table using track changes.
2. Below the table is space to provide feedback and motivation for the entered values.

Table MAIZE *The relative contribution (in %) of the five production factors to the gap between potential and current yields in different regions of the world (see Annex).*

Region	Actual yield (t/ha)	Potential yield (t/ha)	Water	Nutrients	Pests, weed and diseases	Mechani-sation	Knowledge systems
Latin America, Caribbean	3.5	10.0	20	20	10	20	30
North America	9.3	10.5	30	5	15	10	40
Semi-arid Africa, Middle East	3.0	10.1	30	20	20	20	10
Humid Africa	1.6	9.7	10	30	20	20	20
West Europe	9.0	9.6	20	5	15	20	40
Central, Eastern Europe	1.0	9.5	20	20	10	20	30
NE Asia	5.3	6.7	30	10	10	20	30
South Asia	2.1	11.7	10	20	20	20	30
SE Asia	3.2	9.8	10	30	20	20	30

Feed-back and motivation for entered values:

Annex Description of regions

Region	Description
1. Latin America, Caribbean	Mexico, rest of Central America, Brazil, rest of south America
2. North America	Canada, USA
3. Semi-arids of West Asia and Africa	Northern Africa, Western Africa, Eastern Africa, Middle East,
4. Humid Sub-Saharan Africa	Southern Africa
5. Western Europe	OECD Europe
6. Central and Eastern Europe	Turkey, Central Europe
7. CIS	Ukraine, Asia-Stan, Russia
8. Northeast Asia	Korea, Japan
9. South Asia	China, India
10. Southeast Asia	South-eastern Asia, Indonesia
11. Australia, New Zealand and Pacific	Oceania

Annex 2 FAO yields and IMAGE potential yields used in the yield gap analysis

Crop	Region	Actual yield (t/ha)	Potential yield (t/ha)
Wheat	Latin America, Caribbean	2.6	6.5
Wheat	North America	2.6	8.2
Wheat	Semi-arid Africa, Middle East	2.1	6.0
Wheat	West Europe	5.7	6.4
Wheat	Central, Eastern Europe	3.0	6.8
Wheat	CIS	2.0	7.7
Wheat	NE Asia	4.5	5.2
Wheat	South Asia	2.6	5.1
Wheat	Australia, New Zealand, pacific	1.3	6.4
Maize	Latin America, Caribbean	3.5	10.0
Maize	North America	9.3	10.5
Maize	Semi-arid Africa, Middle East	3.0	10.1
Maize	Humid Africa	1.6	9.7
Maize	West Europe	9.0	9.6
Maize	Central, Eastern Europe	1.0	9.5
Maize	NE Asia	5.3	6.7
Maize	South Asia	2.1	11.7
Maize	SE Asia	3.2	9.8
Rice	Latin America, Caribbean	4.2	9.7
Rice	Humid Africa	1.6	10.8
Rice	NE Asia	6.3	7.1
Rice	South Asia	3.3	9.0
Rice	SE Asia	3.9	9.9
Potato	West Europe	34.6	36.9
Potato	Central, Eastern Europe	14.3	39.6
Potato	CIS	12.7	43.7
Barley	Semi-arid Africa, Middle East	1.5	4.3

Crop	Region	Actual yield (t/ha)	Potential yield (t/ha)
Barley	West Europe	4.4	4.9
Barley	Central, Eastern Europe	2.4	5.4
Barley	CIS	1.8	6.9
Barley	Australia, New Zealand, pacific	1.6	6.4
Cassava	Humid Africa	9.5	39.2
Cassava	SE Asia	17.0	33.9
Cotton	North America	2.4	3
Cotton	Semi-arid Africa, Middle East	2.0	3.3
Cotton	South Asia	1.3	3.3
Dry beans	Latin America, Caribbean	0.8	5.1
Dry beans	Humid Africa	0.5	5.4
Dry beans	South Asia	0.3	5.6
Ground nut	Humid Africa	1.3	5.4
Oil palm	Humid Africa	2.7	24.0
Oil palm	SE Asia	19.0	32.0
Rapeseed	North America	1.7	5.4
Rapeseed	West Europe	3.1	5.0
Rapeseed	Central, Eastern Europe	2.0	5.3
Rapeseed	South Asia	1.1	5.0
Rapeseed	Australia, New Zealand, pacific	1.0	5.6
Soybean	Latin America, Caribbean	2.5	5.1
Soybean	North America	2.7	5.4
Soybean	NE Asia	1.7	3.8
Soybean	South Asia	1.1	5.6
Sugarcane	Latin America, Caribbean	72.7	84
Sugar beet	Western Europe	63.4	80
Tropical cereals	Semi-arid Africa, Middle East	0.7	7.6
Tropical cereals	Humid Africa	1.3	8.2
Tropical cereals	South Asia	0.9	8.7

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