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Technology options for feeding 10 billion people

Plant breeding and innovative agriculture

Study

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Abstract

In the frame of the STOA project "Technology options for feeding 10 billion people", this report analyse how farming management concepts, practices and technologies, including plant breeding, could enable sustainable intensification of crop production, with the aim to increase food production and support food supply. The aim of sustainable intensification is to produce more food from the same area of land while reducing the environmental impacts, under social and economic beneficial conditions.

The study addresses agriculture in developing countries as well as in industrialized countries (Europe), small-scale and large-scale farming, extensive and intensive agricultural production systems, and low and high tech production practices. The main topics are:

- Reducing yield gaps – sustainable intensification and improving crop management;
- Increasing yield potentials – plant breeding;
- Reducing crop losses – improving harvest and postharvest procedures.

For these topics, options for action are identified and discussed.

CONTENTS

LIST OF ABBREVIATIONS

AKIS	Agricultural Knowledge and Innovation System
AKS	Agricultural Knowledge System
AWU	Annual Work Unit
Bt	Bacillus thuringiensis
CA	Conservation Agriculture
CAP	Common Agricultural Policy
CoP	Community of Practice
CTF	Controlled Traffic Farming
DNA	Deoxyribonucleic acid
EAFRD	European Agricultural Fund for Rural Development
ECS	Evaporating Cooling System
EIP	European Innovation Partnership
EPO	European Patent Office
ESU	European Size Unit
EUROSTAT	Statistical Office of the European Union
FADN	Farm Accounting Data Network
FAO	Food and Agriculture Organisation of the United Nations
FFS	Farm Structure Survey
FFV	Fresh Fruits and Vegetables
FSC	Food Supply Chain
GAO	Gross Agricultural Output
GMO	Genetically Modified Organism
GHI	Global Hunger Index
GNSS	Global Navigation Satellite Systems

HNV	High Nature Value (farming)
INM	Integrated Nutrient Management
IPM	Integrated Pest Management
IPR	Intellectual Property Rights
JRC	Joint Research Cenre (of the European Commission)
K	Potassium
LFA	Less Favoured Area
LINSA	Learning and Innovation Networks for Sustainable Agriculture
LSU	Livestock Unit
MAP	Modified Atmosphere Packaging
MAS	Marker Assisted Selection
NGO	Non-Governmental Organisation
NUE	Nitrogen Use Efficiency
PA	Precision Agriculture
PPB	Participatory Plant Breeding
N	Nitrogen
OF	Organic Farming
PBR	Plant Breeders' Right
PCR	Polymerase Chain Reaction
PVP	Plant Variety Protection
PS	Phenotypic Selection
P	Phosphorous
QTL	Quantitative Trait Loci
RAPD	Random Amplified Polymorhic DNA
RA	Regular Air/Atmosphere
RBMP	River Basin Management Plan

RH	Relative humidity
RNA	Ribonucleic Acid
SCAR	Standing Committee on Agricultural Research
SGM	Standard Gross Margin
SMART	Selection with Markers and Advanced Reproduction Technologies
SNP	Single Nucleotide Polymorhism
SOC	Soil Organic Content
SOM	Soil Organic Matter
SRI	System of Rice Intensification
SSR	Sort Simple Repeats, also called Microsatellites
UAA	Utilised Agricultural Area
UPOV	International Union for the Protection of New Varieties of Plants
ULO	Ultra Low Oxygen
USPTO	US Patent and Trademark Office
TILLING	Targeting Induced Local Lesions In Genoms
WFD	Water Framework Directive

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EXECUTIVE SUMMARY

The objective of this study is to analyse how farming management concepts, practices and technologies, including 0plant breeding technologies, could enable sustainable intensification of crop production, with the aim to increase food production and support food security. The scope of the study encompass agriculture in developing countries as well in industrialized countries (Europe), small-scale and large-scale farming, extensive and intensive agricultural production systems, and low and high tech production practices. The assessment is restricted to crop production. The main topics are:

> Reducing the yield gap – sustainable intensification and improving crop management
> Increasing the yield potential – plant breeding
> Reducing crop losses – improving harvest and postharvest procedures

Sustainable intensification and improving crop management: Reducing the yield gap

Many regions worldwide show large yield gaps, which is the difference between yield potential and average farmers' yields. Under changing environmental conditions, three objectives of improved crop production are important:

> Higher production by better exploring the (genetic) yield potential
> Better input use by higher production efficiency
> Increasing the site specific yield potential by improved land productivity

Sustainable intensification means producing more food from the same area of land while reducing the environmental impacts, under social and economic beneficial conditions.

Crop production systems include every step in cultivation, from rotation, tillage and sawing to crop harvest, and compromise a set of common principles, technologies and management practices. Crop production systems with the potential for sustainable intensification are:

> *Precision agriculture*: Precision Agriculture aims to apply the right treatment in the right place at the right time. It is an innovative information controlled management concept of crop production, based upon various new or advanced technologies. These include in particular satellite-supported positioning systems, sensor technologies for data collection, geo-information systems, various rate applications and decision support systems.

> *Conservation agriculture*: The three key principles of conservation agriculture are continuous no or minimal mechanical soil disturbance, permanent organic-matter soil cover and diversified crop rotations. Conservation agriculture aims to prevent soil degradation und to preserve and/or enhance soil fertility by strengthening natural biological processes above and below the ground.

> *System of rice intensification*: This innovation in rice production systems is basically a set of modified practices for managing rice plants, and the soil, water and nutrients that support their growth, starting as a civil society innovation. In the meantime, the approach is also transferred to other crops.

> *Organic farming*: Organic agriculture is defined by international principles and standards. Major aims are a more efficient nutrient use and re-use by optimising the scope of nutrient recycling, and the exploitation of agro-ecological mechanisms. Especially readily soluble mineral fertilisers, synthetic pesticides and performance stimulants are renounced. Organic Farming is at first a legally defined production method for food and may also be part of movements with agro-political and ideological-philosophical influence.

> *Agroforestry*: Agroforestry systems are understood as land use systems which simultaneously combine deliberately interplanted annual crops and trees. Agroforestry consists of a set of reasoning and design principles rather than fixed planting schemes. Agroforestry aims to diversify and sustain production. There are countless Agroforestry systems that have been developed across the globe.

- *Integrated crop-livestock production systems*: They are farming systems in which livestock and crops are produced within a co-ordinated framework. In many mixed systems, the waste products of one component serve as a resource for the other: manure from livestock is used to enhance crop production, whilst fodder crops, crop residues and by-products feed animals.

Just as worldwide, farming systems in the EU differ strongly, from semi-subsistence farming to specialist and intensive, larger-scale crop farming and to large-scale corporate farming. The discussed crop production systems have variable relevance and potential in specific farming systems. Generally, the overall principles of the crop production systems have to be locally adopted to the agro-ecological and socio-economic conditions of farms.

Likewise, the three main objectives of sustainable intensification are addressed in different ways. Precision Agriculture addresses especially high external input agriculture and specialised crop production, and intends in the first of all to make crop production more efficient and environmental-friendly. In contrast, the central objective of the other discussed crop production systems is to improve the site specific yield potentials, with maintenance and enhancement of soil fertility in the centre. They imply deeper changes in crop production systems: diversified crop rotations, plant associations, green manure and permanent organic-matter soil cover, and/or integration of crop and livestock production. All systems have the potential for higher yields and productivity. Therewith, they can reduce yield gaps.

Despite all differences between the crop production systems, some important trends in the frame of sustainable intensification can be identified:

- Increasing differentiation of crop management
- Higher complexity of management concepts
- Agriculture gets more knowledge-intensive
- Shift to system approaches
- Mainstreaming of agro-ecological approaches
- Combination of bottom-up and top-down approaches

Plant breeding: Increasing the yield potential

In the past, plant breeding made, by enabling higher yields, a major contribution to better food supply and to the fact, that the increasing crop production mostly took place on already cultivated land. This part of the study gives an overview of the development of plant breeding as an applied science, the fundamental background of inheritance, the conventional plant breeding methodologies and the state of the art of new approaches. In the last decade, the knowledge about the genetic background of inheritance of diverse traits for agronomical important crop has increased remarkably.

Plant breeding is confronted with a multiplicity of sophisticated breeding goals. They can be summarised by three main goals that have to be achieved for crop improvement:

- Increasing yield potential
- Safeguarding yield
- Quality of products
- Every plant breeding approach follows three general steps, including:
- Creation of a new initial genetic variation
- Selection of suitable genotypes for creating new varieties
- Testing, maintenance and reproduction of a variety

Conventional plant breeding methodologies depend on the particular crop plant species and its propagation type. The type of propagation determines the different breeding strategies and the resulting major types of varieties: pure-line, population, clonal and hybrid varieties. They dominate the cultivated areas worldwide. Since the 1990s, varieties have been generated by genetic modification (GM crops) which made the transfer of genes from any genome possible. They are cultivated mainly in North and

South America, China and India. Currently, two traits (herbicide tolerance, insect resistance) and four major cash crops (cotton, maize, rapeseed, soybean) are dominating the area cultivated with GM crops. New approaches such as cisgenic and intragenic breeding are in development.

Additionally, nowadays a number of well-established modern tools applicable for each of the three major breeding steps respectively are available:

> Tissue culture-based methods
> Marker-assisted breeding
> Mutation breeding

Lastly, two plant breeding approaches are described which aim to increase yield potential in low external input agriculture and to provide varieties adopted to specific local cultivation conditions. “Participatory plant breeding” (PPB) has been developed to better serve the needs of farmers, especially in developing countries, and thereby increase the farmer-breeder-corporation. “Organic plant breeding” aims to provide varieties that are adapted to the conditions of organic farming and take advantage of agro-ecological potentials.

Overall, modern breeding technologies open new possibilities to create genetic variation and to improve selection, but conventional breeding technologies will remain important.

Reducing crop losses

Harvest and postharvest losses are an important issue on the global level. Their reduction can contribute to the local as well as global food security. In this study, food losses until the farm gate are regarded, including handling at harvest and postharvest, storage, transport and distribution by farmers. Although most attention is paid to developing countries in Africa and Asia, the post-soviet countries might experience similar malfunctioning of the food supply system.

The estimates of harvest and postharvest losses vary significantly. A literature survey shows that most of the estimates relate to specific regions, farming systems and food supply chains often under specific weather circumstances of a particular year. Food losses depend on changing food supply chains which include post-harvest technologies and marketing organization and infrastructure. Overall, losses tend to be lower in modern food supply chains of developed countries.

Harvest and postharvest losses can be classified as physiological (caused by environmental conditions), pathological (cause by the attack of pathogens, e.g. fungi, bacteria, insects etc.) and endogenous (caused by endogenous processes like respiration, transpiration, sprouting and ripening). The risk of losses increases with the degree of perishability, from grain, over roots and tubers, to fresh fruits and vegetables. Postharvest losses are closely linked to pre-harvest and harvest technologies. Biological spoilage has its roots in poor protection against pests during the growing period, inadequate timing of harvest and rough handling during harvest and during the transport from the field to the postharvest facilities. Storage of either crop requires controlling temperature and humidity, and often also the content of oxygen and carbon dioxide (grains and FFV). Controlling temperature and atmosphere requires not only facilities but also monitoring and control systems.

Technologies for reducing harvest and postharvest crop losses are available, however, there are number of obstacles to bring them into practice particularly among small poor farmers. These technologies are often not suitable in scale, and they are associated with high investment costs. Most of them require innovations throughout the whole food supply chain. Horizontal and vertical coordination is needed, but there is often no capacity for it.

There are attempts to solve the postharvest problems of small-scale farms by encouraging them to deliver their surplus crop (e.g. cereals, potatoes) as soon as possible into large scale postharvest-storage facilities, usually under conditions regulated by the government. This is generally beneficial, but can have also adverse effects (e.g. improper management).

For poor small-scale farmers and semi subsistence farmers, the way how to reduce postharvest losses remains in improving the traditional technology and enabling their participation in the modern food supply chain. The technological improvements must be of low cost using locally available materials and tailored to the local climatic, natural and socio-economic environment. In addition, producers must be guided to see a clear direct or indirect advantage, particularly the financial benefit.

Modern and improved technologies require knowledge, skill and in many cases effective extension services. Past experience shows that the support system cannot be exclusively technically focused; in contrary, more types of intervention are needed such as providing effective rules, knowledge transfer support, improved access to credits and often direct market intervention providing stabilisation through temporary storage of surpluses. Therewith, government intervention is need.

OPTIONS BRIEF

Spread and implementation of existing knowledge, technology and best practice, and investment in new agricultural science innovation and production system approaches are needed to produce more food in a sustainable way. Overall objective is the contribution of European food production to feed the increasing population worldwide. Sustainable intensification should be reached by

> reducing the yield gap through improving crop production management,
> increasing the yield potential by plant breeding, and
> reducing crop losses.

For these objectives, this study has worked out options for action.

Sustainable intensification in the European Union

Sustainable intensification should consider the very different settings of European farming systems. In consequence, different priority tasks should be talked parallel:

> Increasing input use efficiency especially in intensive production systems to improve their environmental performance and to maintain their production potential;
> Increasing productivity in extensive production systems without compromising their environmental services;
> Including marginalised farmers (e.g., semi-subsistence farming) in productivity improvement to preserve their contribution to food supply and for accompanied social and environmental benefits.

Overall, a stronger focus on maintenance and enhancement of soil fertility and exploitation of agro-ecological mechanism should be taken to stabilize achieved high yield levels in favourable areas, to realise more of existing yield potentials, and to increase the resilience of farming systems. Efforts should be undertaken to explore combinations and mutual benefits between input use efficiency and soil fertility improvement approaches (e.g., precision agriculture and conservation agriculture).

Recent scientific and technological advances and practical experiences offer significant new opportunities to address challenges of crop production in Europe. Sustainable intensification and food security at global and European level demand long-term action. Major steps to enable a contribution of the European agriculture to increasing food production are:

Building awareness

Sustainable intensification needs political commitment at European and Member State level, supported by informed dialogue with farmers and other stakeholders.

More public research funding

After decades of de-investment in public agricultural research, more public money (EU and Member States) is required, in addition to existing research spending. Sustainable intensification will often need specific measures (e.g., public research programmes) to incentivise research that produces public goods and longer-term results.

Prefer system approaches

Crop production systems approaches should be in the centre of research activities. Single technologies and practices promise only restricted advances. Approaches that combine different technologies and practices will produce real progress. Research communities should open up, and mutual learning should be encouraged between precision agriculture, conservation agriculture, organic farming, agroforestry and integrated crop-livestock system research, based on common points in objectives and practices.

Enable long-term projects

Long-term agronomic research projects at both farm and research levels throughout the EU are needed because the impacts of greater shifts in crop production (such as with conservation agriculture, organic farming, agroforestry and integrated crop-livestock systems) needs time to manifest.

Development of sound decision support systems

In precision agriculture, scientifically and economically sound decision support systems are a major bottleneck. Therewith, a research focus should be on precise identification input utilisation factors and yield determining factors, their interaction, and their translation in crop management decision. In general, the relationship between generally valid rules and concrete site specific rules is of high relevance for input efficiency and improved site specific yield potentials.

Address different European farming systems

The European farming systems face different challenges and have specific potentials for sustainable intensification. This should be addressed specifically by agricultural research. Research activities should also include extensive farming and small-scale farming (e.g., semi-subsistence farming) in Europe, to preserve their contribution to food supply, to enhance their productivity and to sustain their environmental and social benefits.

For example, principle of side-specific application of production inputs should be made available for the different European farming systems. Therefore, “soft” Precision Agriculture concepts should be developed which depends mainly on inexpensive technologies or visual observation of crop and soil, and management decision based on experience and intuition. Open question is how high-tech and low-tech approaches could learn from each other.

Strengthening participatory research

For addressing the relevant challenges and encouraging local adoption, interdisciplinary and participatory research should be strengthened. For up-scaling of advanced crop production systems, is, new networks among diverse stakeholders are needed to combine top-down and bottom-up knowledge creation and transfer mechanisms, including institutional learning. This task has to be taken up by the scientific system as well as by funders. At European level, a network “Participatory Research for Global Food Security” could be established in the frame of the Horizon 2020 programme.

Boundaries of the past between public funded basic research and private funded applied research as well as between research institutes and universities as dominant sources of knowledge and innovation and the farmers and commercial sector as adopters get more and more blurred. This demands new forms of cooperation and knowledge exchange. Without public funded incentives for new cooperations, the agricultural knowledge system could become increasingly fragmented.

Revitalise public extension

Effective knowledge and technology transfer to the farming communities, using a combination of scientific and practical expertise, is of high importance. Public funded extension services should be revitalised to increase the skills and knowledge base of agricultural producers breadthwise.

Create incentive programmes

Support in the frame of agri-environmental measures should be implemented for crop production systems with an agro-environmental focus, because the conversion is often connected with initial investments, costs and risks of learning and adapting to local conditions, and delayed improved returns.

Start enabling CAP reform

The direct payments to farmers from the Pillar I of the CAP are neutral in regard to the applied crop production systems. A more enabling surrounding for sustainable intensification would demand a longer-term transformation of the CAP with a phasing out of direct payments, replaced by public payments linked to the provision of societal benefits. Difficulty is to achieve a broad consensus on agricultural production systems which are sustainable or on criteria for environmental-friendly production measures.

Link sustainable intensification with nutrition change

A wider spread of specific agricultural production systems (e.g., organic farming) could support the change of diets with lower consumption of meat products, therewith reducing the high land demand of animal production. Research should further investigate this link, and policies address this issue.

Strengthening plant breeding progress

In the past, plant breeding made a major contribution to increasing yields. In the coming years and decades, further progress is needed in plant breeding which addresses the challenges ahead and different farming systems. Public sector crop breeding and genomics programmes should be initiated that emphasis longer term objectives which cannot be expected from the private sector.

Main focus in public breeding research support should be on marker-assisted selection and SMART breeding as very promising breeding technologies. Additionally, hybrid breeding research remains of high importance and should focus on molecular basis of the heterosis effect and on identifying the best combinations of parental lines for creation of high-performing hybrids.

Organic breeding in the EU is still highly heterogeneous. Progress in organic breeding is needed so that organic farming can take part on overall increase of yield potentials. Modern breeding technologies should be assessed technologies in regard to their compatibility with the principles of organic farming. Strengthening of organic breeding could also be of relevance for other farming systems. Special regulation for the authorization of heterogeneous, locally well adapted varieties should be introduced, and gene sequences of traditional varieties should be excluded from patenting.

Participatory plant breeding was developed and deployed to better serve the needs of small-scale farmers in developing countries. Participatory plant breeding could be an approach to address European semi-subsistence farming which would need public support. Overall, closer collaboration of plant breeders and farmers could become more important in the future with mainstreaming of agro-ecological approaches and more local differentiation of crop management.

New plant breeding techniques (such as cisgenesis/intragenesis) are associated with legislative uncertainties of the GMO classification. Contrary opinions on the legal status are developing in science and society. Therefore, a broad dialogue should be initiated with the aim to clarify the legal status of new plant breeding techniques in the frame of the GMO regulation.

Concern is that the increasing number of patents on basic tools for genetic modification and marker-assisted breeding in the hand of a small number of companies will hinder plant breeding innovations. Therefore, the public and non-profit research sector should support initiatives to create platforms for open innovation, using open source approaches.

Reducing crop losses

Harvest and post-harvest losses are an important issue on the global level. Their reduction can contribute to the local as well as global food security. Food losses until the farm gate include handling at harvest and postharvest, storage, and transport and distribution by farmers. The amount of food losses is dependent from natural factors like climate, weather, crop biological characteristics and spread of pests, and on the development state of food supply chains, with their specific post-harvest technologies, marketing organization and existing infrastructure.

For reducing crop losses (particularly in developing countries and transition countries), awareness among farmers and the other actors in the food supply chain should be increased. Long-term strategies should be established by international bodies, national and regional authorities as well as non-governmental donor organisations. Strategies should be tailored to their nature and causes, to the affected crops and to beneficiaries and their socio-economic characteristics. Private and public research and development should focus on selection of cultivars resistant or less susceptible to pests, biopesticides (particular against fungal pest producing mycotoxins), and small scale technical equipment.

Next important point is the provision of methodological guidelines and training on good practices, tailored to particular crops (taking into account differences among cultivars), locality and human and financial capacities of beneficiaries (e.g., subsistence farmers, commercial farmers). Equally important is the exchange of experience among farmers and information flows along food supply chains as essential elements of crop losses programmes; similarly, horizontal and vertical cooperation is needed.

Marketing system should be improved by government and local authorities, to support the spread of promising technologies by functioning food supply chains. Incentives should be given for the development of rural markets in their specificities, supplementary to urban and export oriented food markets.

Finally, infrastructure such as roads and railways should be enhanced, but attention should also be paid to clean water supply, energy supply and ICT (internet, mobile phone).

1. BACKGROUND AND APPROACH

1.1. Background

Access to sufficient, safe and nutritious food is a fundamental human right (UN Human Rights 2010), yet the number of undernourished people worldwide is unacceptably high and pervasive. Increased investments in agriculture from the 1960s to the 1980s in the developing world and the associated growth in food production and decrease in relative food prices enabled a remarkable decrease in the proportion and total number of hungry people, despite a strong growing world population. But since the mid 1990s, the overall number of undernourished has increased once again, and with the food and economic crisis from 2007 to 2009, the percentage of hungry people worldwide increased as well (Meyer et al. 2011). Global food insecurity is a chronic problem and future perspectives are at least uncertain. Major challenges for food security – respectively food supply – are (Meyer et al. 2011; Royal Society 2009):

> Increasing global population
> Nutrition transition (growing demand for livestock products)
> Growing overall demand for biomass (e.g. demand for biofuels)
> Slowing of increases in agricultural productivity
> Climate change (adaptation and mitigation needs)
> Natural resource management (increasing threatening of soil and biodiversity, scarcity of water and land)
> Importance of smallholders for a pro-poor development

In this context, the STOA project „Technology options for feeding 10 billion people" aims to investigate und assess technology options to address the challenge of sufficient food supply in the coming decades. The project compromise three parts:

> Sustainable intensification of crop production (area 1 + 2)
> Sustainable food storage, processing and packaging (area 3)
> Tackling crop and food losses and waste (area 4 + 5)

The study „Technology options for plant breeding and for innovative agriculture" (area 2) investigates improvements in crop production, as part of the overall investigation of the food chain.

1.2. Objective, scope and topics

The objective of this study is to analyse how farming management concepts, practices and technologies, including plant breeding technologies, could enable sustainable intensification of crop production, with the aim toincrease food production and support food security. Therewith, animal production is not part of the study.

Additionally, interplay of agriculture and climate change respective biodiversity is not part of this study and will be assessed in study 1. Nonetheless, plant breeding and innovative crop production approaches address climate change und biodiversity issues and impacts of options on climate change und biodiversity will be assessed.

The study addresses agriculture in developing countries as well in industrialized countries (Europe), small-scale and large-scale farming, extensive and intensive agricultural production systems, and low and high tech production practices. Three main topics are covered in the study:

> Topic 1: Reducing the yield gap – sustainable intensification and improving crop management
> Topic 2: Increasing the yield potential – plant breeding
> Topic 3: Reducing crop losses

1.3. Approach

1.3.1. Approach in topic 1

The actual grain yields in some regions (e.g., North-western Europe) are already near the maximum possible yields which can be achieved with the regional environmental conditions and the genetic potential of available varieties. However, many other regions show large yield gaps, which is the gap between the yield potential and actual production per hectare. Therefore, there is potential for increasing production from already cultivated land and existing cultivars, independent from the progress in plant breeding.

Farming management concepts, practices and technologies for sustainable intensification will be evaluated in two steps. These are:

> crop production systems and

> specific technologies and practices.

Crop production systems include every step in cultivation, from soil preparation and sawing to crop harvest, compromising a set of farming technologies and management practices. For some agricultural production systems, an explicit definition is existing, and for all systems, principles for agricultural practices as well as soil and ecosystem management are formulated. Relevant crop production system approaches for sustainable intensification to be investigated are (STOA 2009; FAO 2011a; Worldwatch Institute 2011):

> Precision agriculture

> Conservation agriculture

> System of rice intensification

> Organic farming

> Agroforestry

> Integrated crop-livestock production systems

These production systems share partly specific farming technologies and practices. Additionally, combinations of these production systems are emerging, such as Conservation Agriculture with trees or Evergreen Agriculture (Garrity et al. 2010) or Climate-Smart Agriculture (FAO 2010b).

In the second step, *specific farming technologies and practices*, which are part of the production systems, will be analysed in more detail. These are existing and emerging technologies and practices for

> overall crop production management,

> soil management,

> water management,

> nutrition management,

> pests, diseases and weed control management.

Leading questions for the assessment of the identified and described production systems and technologies/practices period are:

> Which chances exist for adaptation and implementation under different farming systems?

> Which contribution to an increased production can be expected?

> Which contribution tohigher production efficiency can be expected?

> Which contribution toimproved land productivity can be expected?

The aim of the study is to assess sustainable intensification at the global and European level. The *broad scope and global perspective* of the study demands the development of a multidimensional assessment scheme. For answering the questions, relevant differentiations are:

> Geoecological region: Tropics, Subtropics, Mediterranian and temporate regions;

- State of economic development: developing countries and industrialized countries (Europe), respective agricultural-based countries, transforming countries and urbanized countries (World Bank 2007, pp. 29-38);
- Structure of the agricultural sector: small-scale and large-scale farming;
- Use of external inputs in crop production: extensive and intensive agricultural production systems;
- Technology level in crop production: low tech and high tech production practices.

These different dimensions will be captured with a *farming system approach*. A farming system is defined as a population of individual farms that have broadly similar resource bases, enterprise patterns, household livelihoods and constraints. A strongly simplified scheme of farming systems (based on Dixon et al. 2001; Hazell, Wood 2008) is used to cover this fast diversity of global agriculture:

- *Extensive small-scale farming in developing countries*: low/non use of external inputs, without irrigation, bad infrastructure – e.g. many countries in Africa;
- *Intensive small-scale farming in developing countries*: high use of external inputs, with irrigation, better infrastructure – e.g. part of agriculture in East and South Asia;
- *Industrialized large-scale farming in developing countries*: high use of external inputs, good infrastructure, plantations – e.g. countries in Latin America;
- *Extensive farming in Europe*:less favoured areas, relative low use of external inputs, areas of agro-environmental measures, organic farming;
- *Intensive farming in Europe*:sites of high productivity, high use of external inputs, restricted number of planted crops.

For a more detailed assessment of agricultural production systems and technologies in the EU, a second simplified scheme of farming systems was developed. Five farming systems in the EU were identified which represent the most important typical farming situations in crop production. Therewith, not all existing farm types in the EU are covered. Criteria for the selection of the farming systems are farm size, production intensity, specialisation and integration in food chains. Additionally, the identified five farming systems represent different dominant regional settings of farming in the EU. Annex C gives a detailed description. These EU farming systems are:

- *Extensive small-scale, semi-subsistence farming*: Over 40% of all holdings in EU-27 produce food for the family and relatives, only surplus goes to the market. This farming system is only of any importance in the new Member States and Mediterranean countries, with Romania as the most important. The small-scale farms apply extensive production methods, partly without external inputs.
- *Extensive farming in less favoured areas*: 54% of all farms in EU-27 are located in less-favoured areas. Less favoured areas cover over 50% of the total agricultural area in Czech Republic, Ireland, Greece, Spain, Italy, Hungary, Malta, Austria, Portugal, Slovenia, Slovakia and Finland. Farming in less favoured areas is characterised by extensive production systems respectively traditional land-use systems, often based on grazing livestock. But cereal production is also important in less favoured areas.
- *Medium intensive, mixed farming systems*: Mixed farming systems combine crop and livestock production in different patterns and have a relatively low specialisation. Around 13% of all farms in EU-27 are mixed farms. Mixed farming systems occupy over 10% of the total utilised agricultural area in Belgium, Czech Republic, Denmark, Germany, France, Latvia, Lithuania, Hungary, Poland, Portugal, Romania, Slovenia and Slovakia.
- *Intensive, larger-scale crop farming*: The regions with concentrated cereal and specialised crop production are at the same time the areas with a high degree of larger-scale farms. Larger-scale farming, based on high external inputs, is associated with low-land areas with high productivity.

High input farm types are predominant in the Netherlands, Belgium, south-eastern England, northern France, north-western Germany, northern Italy and northern Greece.

> *Large-scale corporate farming*: Large-scale corporate farming compromise production cooperatives and various types of farming companies. They are result of the transition process in Central and East Europe since 1990. Corporate farms held over 50% of the total agricultural area in Bulgaria, Czech Republic and Slovakia. Large corporate farms tend to specialise in cereals and oilcrops.

1.3.2. Approach in topic 2

In the past, plant breeding made a major contribution to higher food supply and to the fact, that the increasing crop production mostly took place on already cultivated land. In the future, success in plant breeding is needed as an important baseline for higher yields and increasing production. At the same time, plant breeding must contribute to climate change adaptation, higher production efficiency and more environmental-friendly agricultural production systems.

Overall, the assessment of breeding technologies will be based on a breeding in production system approach. Therewith, the assessment will look at the suitability of breeding technologies for different crops, production system approaches and farming systems.

In the first step, breeding technologies are classified and described, based on a short overview of the history of plant breeding, and on basics of breeding steps and goals. The following groups of breeding technologies are included:

- Conventional breeding (including hybrid seeds)
- Mutation breeding
- Tissue culture techniques
- Marker assisted breeding
- Breeding with genetic modification of crop plants
- Breeding in organic farming
- Participatory plant breeding

These plant breeding technologies are assessed in regard to

- their relevance for the main breeding steps,
- their current status in research and practical application,
- their relevance for different important crop plants,
- their relevance for different breeding goals, and
- their adaptability in the different farming systems.

Legal requirements such as GMO regulation and intellectual property rights are discussed. Additionally, a short overview on seed industry and markets is given.

1.3.3. Approach in topic 3

Postharvest losses of staple foods (non-perishable food crops) in industrialized countries are generally considered to be low and are not considered significant under normal circumstances. In developing countries, postharvest handling and storage are stages in the food supply chain of staple foods with relatively high food losses. Fresh fruits and vegetables (horticultural products) generally suffer higher loss rates within industrialized and developing countries, although at different points in the food supply chain and for different reasons.

This topic concentrates on developing countries. Additionally, the problem of crop losses in Central and Eastern European countries is included. The focus of this study is on three categories of crops: grains (cereals and oilseeds), roots and tubers and fresh fruits and vegetables (FFV).This topic regards the losses in the food supply chain until farm-gate: harvest, postharvest handling and storage, transport and distribution by farmers. Losses before harvest are part of the yield gap (e.g. losses due to pests) and will be discussed in topic 1.

The analysis starts with an overview of harvest and postharvest crop losses. In the next step, causes of crop losses are analysed. Based on this, technology and of non-technology optionsto reduce harvest and postharvest crop losses in the grain sector, the root and tuber sector and the fresh fruits and vegetable sector are assessed, and obstacles to bring them into practice are outlined. A special focus is given moulds and mycotoxins. Finally, institutional and other socio-economic aspects are discussed.

2. OVERVIEW GLOBAL AND EUROPEAN AGRICULTURE

This chapter gives a short overview on crop production, development of productivity and the diversity of framing structures worldwide and in the European Union, as baseline for the assessment of approaches for sustainable intensification, plant breeding and reducing crop losses.

2.1. Crop production

Global crop production

Cereals are the major source of food supplies for direct human consumption, occupying around 55% of the overall harvested area worldwide (Table 1). Currently, 2.4 billion tonnes of cereals are produced (FAO 2012a, p. 184). Over the last five decades, cereal production increasingly concentrated in Asia (Beddow et al. 2010, p. 22). The production of *rice* (paddy) accounted for 672 million tonnes, on 164.1 million ha[1]. The bulk of world rice production is destined for food use, although some quantities are used in domestic animal feeding. Rice is the primary staple for more than half the world's population, with Asia representing the largest producing and consuming region[2]. In recent years, rice has also become an important staple throughout Africa (FAO 2012a, p. 184).

With 220.4 million ha (2011), more of the earth's surface is covered with *wheat* than with any other food crop. World output of wheat stands at around 651 million tonnes[3]. Wheat is second to rice as the main food crop. Around 70% is used as food, 19% for animal feed and the remaining 11% is used in industrial applications, including biofuels. Wheat production is mainly located in the temperate zones of developed and emerging countries[4] (FAO 2012a, p. 186).

Maize is the world's primary coarse grain, produced on 170.4 Mio. ha (2011). Maize accounts for 74% of aggregate coarse grain output of 1.1 billion tonnes[5] (2010). Maize has the ability to grow in diverse climates. Production is concentrated in North America, especially the USA, South America and China[6]. Around 55% of world consumption of coarse grains is used for animal feed. At the global level, about 17% of coarse grains is devoted to food, but the share rises to 80% in Sub-Sahara Africa. There, maize, millet, sorghum and other coarse grains (e.g. tef in Ethiopia) account for 3 out of every 4 kg of cereals consumed as food. Almost 40% of maize – 111 million tonnes – is used for biofuel production, an eight-fold increase in just ten years (FAO 2012a, p. 186).

Production of *oilcrops* has seen the most rapid growth in the last decades (Table 1). *Soybeans*[7], rapeseed and sunflower are the major oilcrops in temperate zones, while palmoil is the major oilbearing crop in the tropics, increasingly cultivated in Southeast Asia. Around 168 million tonnes of oilseeds and oil-bearing crops were produced in 2010, on 272.7 million ha (2011). Overall, four oilcrops (palmoil, soybeans, rapeseed and sunflower seed) now account for 75% of the world production[8]. A major driving force has been the growth of food consumption in developing countries, mostly in the form of vegetable oil. The demand for protein meals for animal feed has contributed to changes in the geographical distribution of oilseed production. The latter has shifted towards countries that could produce and

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[1] Global harvested area, production and yields of rice: Figure A2 – A5 in Annex A

[2] Global geographic distribution of rice production: Figure A1 in Annex A

[3] Global harvested area, production and yields of wheat: Figure A8 – A11 in Annex A

[4] Global geographic distribution of wheat production: Figure A1 in Annex A

[5] Global harvested area, production and yields of maize: Figure A19 – A23 in Annex A

[6] Global geographic distribution of maize production: Figure A18 in Annex A

[7] Global geographic distribution of soybean production: Figure A18 in Annex A

[8] Global harvested area, production and yields of soybean: Figure A26 – A29 in Annex A
Global harvested area, production and yields of rapeseed: Figure A33 – A36 in Annex A
Global harvested area, production and yields of sunflower seed: Figure A40 – A43 in Annex A

export oilseeds of high protein content, in which oilmeals are not by-products but rather joint products with oil, e.g. soybeans in South America (FAO 2012a, p. 188).

Table 1: Global harvested area by crop category

Crop category	Area (million ha)	
	1961	2011
Cereals	648.0	697.7
Oil crops	113.4	272.7
Pulses	64.0	78.1
Root crops	47.6	54.3
Fibre	38.7	38.4
Fruits	24.5	57.1
Vegetables	23.7	56.7
Citrus fruits	2.3	9.3

Source: Beddow et al. (2010), p. 21; FAOSTAT (2013)

Pulses are an important constituent in local food crops in developing countries. They are a key source of protein in the diets of the world's poorest countries. In India, the commodity forms an important staple in vegetal-based diets. In crop production systems, pulses represent an input-saving and resource-conserving technology through biologically fixing nitrogen. Around 68 million tonnes of pulses were produced in 2010, on 78.1 million ha (2011)[9]. Production is geographically diverse (FAO 2012a, p. 190).

Root crops have traditionally been a staple in several countries, mainly in Sub-Sahara Africa, Latin America and the Caribbean. Potato[10] is the main root crop in temperate zones, while in the tropics, a broad array is cultivated, with cassava[11] as the major root crop. *Cassava* plays a twin role as a food security and industrial crop. 726 million tonnes of roots and tubers were produced in 2010, on 54.3 million ha (2011). This commodity group exhibit the most divergent trends in production across regions and economic status (FAO 2012a, p. 192).

Currently 166 million tons of *sugar* (raw equivalent) are produced in 120 countries. Over 70% of sugar is derived from sugar cane (tropic zones) and the remainder from sugar beet (temperate zones)[12]. The harvested area is 30.5 million ha (2011). The total acreage of *sugar cane* cultivation has doubled in the past 25 years. In Brazil, the world's leading producer, well over half of the crop is used in ethanol production. On the other hand, higher production volumes in India reflect the importance of sugar in domestic diets. Sugar beet production in the developed countries declined since the 1980s (FAO 2012a, p. 196).

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[9] Global harvested area, production and yields of pulses: Figure A47 – A49 in Annex A

[10] Global harvested area, production and yields of potato: Figure A53 – A56 in Annex A

[11] Global harvested area, production and yields of cassava: Figure A6059 – A62 in Annex A

[12] Global harvested area, production and yields of sugar beet: Figure A63 – A66 in Annex A

Global *fruit and vegetable* production experienced a remarkable increase over the last decades (Table 1). The high value of fruits and vegetables is not just limited to their monetary value, as they play a highly important role in improving the diets of people around the world. Worldwide, over 600 million tonnes of fruit and around 1 billion tonnes of vegetables were produced. The global cultivation for fruits is 57.1 million ha and for vegetables 56.7 million ha (2011). World production has been fuelled by an area expansion in Asia, especially in China. Strong growth rates in fruit and vegetable cultivation have also been recorded in food-insecure and low-income regions, such as in Sub-Sahara Africa and in South Asia (FAO 2012a, p. 194).

Crop production in the European Union

The total agricultural area covered 172 million hectare in the EU-27 in 2007, of which 60.5% was arable land, 32.9% permanent grassland, 6.4% permanent crops, and 0.2% kitchen gardens[13]. Several Member States (Greece, Spain, Italy, Cyprus) have a much higher proportion of permanent crops than the EU average (EUROSTAT 2012c). Cereals are the major field crop (Table 2), occupying two third of the harvested area in the EU in 2011, followed by oil crops[14] (FAOSTAT 2013). The EU-27 produced 282.9 million tonnes of cereals including rice[15] in 2010. Almost half (48.6%) of the total production of cereals was accounted for by wheat[16], while around one fifth of the total was composed of grain maize[17] (19.9%) and barley[18] (18.3%). France and Germany were by far the largest cereal, sugar beet and oilseed producers, together accounting for more than half of the EU-27's sugar beet production[19] (53.1%), and just under two fifth of its oilseeds production (38.9%) and of its cereal production (37.3%) in 2011 (EUROSTAT 2012d). France and Spain are the most important producers of pulses[20]. The leading potato producer in the EU are Germany, Poland, France and the Netherlands[21].

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[13] Arable land, permanent crops, permanent grassland, kitchen gardens and total land area by Member States: Figure A69 in Annex A

[14] EU production area, production and yields of soybean: Figure A30 – A32 in Annex A
EU production area, production and yields of rapeseed: Figure A37 – A39 in Annex A
EU production area, production and yields of sunflower seed: Figure A44 – A46 in Annex A

[15] EU production area and production of rice: Figure A6 – A7 in Annex A

[16] EU production area, production and yields of wheat: Figure A12 – A14 in Annex A

[17] EU production area, production and yields of maize: Figure A23 – A25 in Annex A

[18] EU production area, production and yields of barley: Figure A15 – A17 in Annex A

[19] EU production area, production and yields of sugar beet: Figure A67 – A69 in Annex A

[20] EU production area, production and yields of pulses: Figure A50 – A52 in Annex A

[21] EU production area, production and yields of potato: Figure A57 – A59 in Annex A

Table 2: Harvested area European Union by crop category in 2011

Crop groups	Area (million ha)	Percentage (%)
Cereals	56,4	65,7
Oil crops	16,9	19,7
Pulses	1,5	1,7
Root crops	1,9	2,2
Fibre	0,5	0,6
Fruits	5,8	6,8
Vegetables	2,3	2,7
Citrus fruits	0,5	0,6

Source: FAOSTAT (2013)

In the EU-27, the most important vegetables in terms of production were tomatoes, onions and carrots, while the most important fruits were apples, oranges and peaches. Italy and Spain were the largest producers of vegetables and fruits among the EU Member States (EUROSTAT 2012d).

2.2. Development of productivity

Global development of productivity in crop production

From the 1950s, major achievements in agricultural production took place, with high average growth rates of yields due to the increasing use of high-yielding varieties, synthetic fertilizers, pesticides, irrigation and mechanization. Worldwide, the average rates if yield growth were lower in 1990-2007 than in 1961-1990 (Table 3). The growth of wheat yields slowed the most, and for the high-income countries as a group, wheat yields barely changed over the 1990-2007 period. Rice and soybean yields grew only around 1% per year in the last two decades. Corn showed a relative low decrease of yield growth. As an exception, the low-income countries have seen increasing rates of growth in wheat and rice yields (Alston et al. 2010, p. 48).

Table 3: Global yield growth rates (% per year) for selected crops, 1961-2007

Group	Corn		Wheat		Rice		Soybeans	
	1961-1990	**1990-2007**	**1961-1990**	**1990-2007**	**1961-1990**	**1990-2007**	**1961-1990**	**1990-2007**
World	2.20	1.77	2.95	0.52	2.19	0.96	1.79	1.08
North America	2.20	1.40	2.23	0.01	1.67	1.54	1.05	0.04
West Europe	3.30	1.81	3.31	0.63	0.38	0.55	1.64	0.05
East Europe	1.91	0.97	3.18	-1.69	-0.41	1.07	1.90	2.29
High per capita income countries	2.34	1.48	2.47	0.06	1.07	0.54	1.14	0.02
Middle per capita income countries	2.41	2.12	3.23	0.85	2.54	0.81	3.21	2.08
Low per capita income countries	1.07	0.65	1.32	2.15	1.46	2.16	2.63	0.00

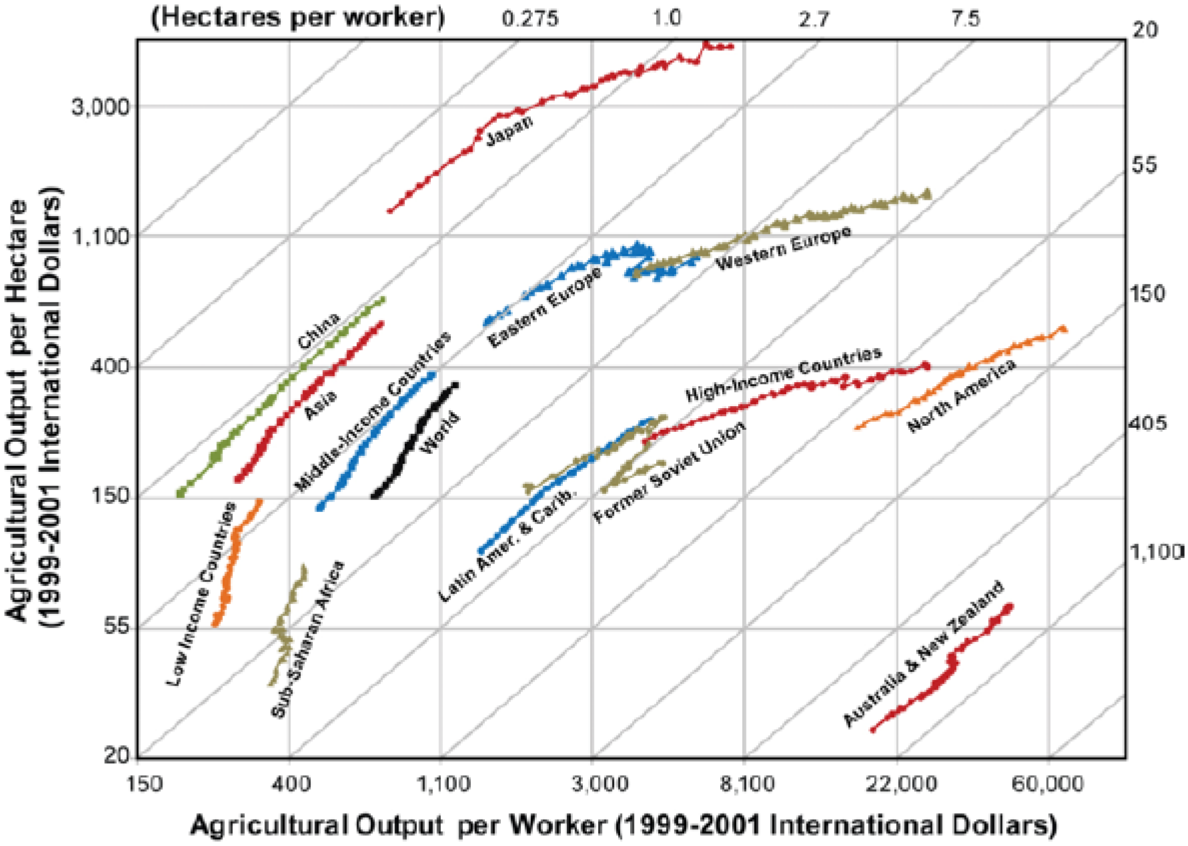
Source: Alston et al. (2010), p. 49

Changes in global and regional yield aggregates can be influenced by changing spatial location of production. Changes in location of production imply changes in average productivity (yields) to the extent that different locations have different endowments of soils and climate, different economic incentives, and different technological opportunities (Alston et al. 2010, p. 50).

In parallel with the declining yield growth rates, the longer-run growth in land productivity (aggregated output per harvested area) and labour productivity (aggregated output per agricultural worker) show a slowdown in the rate of growth during the post-1989 period compared with the previous three decades worldwide (Alston et al. 2010, p. 52). Exception is China which experienced a significant increase of land and labour productivity growth in the last two decades.

The development of land and labour productivity and land-to-labour ratio over time for different regions shows figure 1. The horizontal axis measures labour productivity (in logarithms) and the vertical axis measures land productivity (in logarithms).The diagonals indicate constant land-to-labour ratios, measured in hectares per agricultural workers (in logarithms). As the productivity locus for a particular country or region crosses a diagonal from left to right, it indicates a decrease in the number of economically active workers in agriculture per harvested hectare in that region (Alston et al. 2010, p. 53).

Figure 1: **Land and labour productivity by region, 1961-2005**



Source: Alston et al. (2010), p. 54

Land-to-labour ratios reflect the very different farming structures (Chapter 2.3) and range from around one hectare per worker (China) to over 500 hectares per worker (Oceania). In Japan's case, land-labour ratios rose from 0.6 hectares per worker in 1961 to 1.6 in 2005. Land-labour ratios in Australia and new Zealand have changed little, whereas they have risen significantly in North America and Western Europe. In contrast, Sub-Sahara Africa has become much more labour-intensive, so its land-labour ratios have declined from 10 hectares per agricultural worker in 1961 to 5 hectares in 2005 (Alston et al. 2010, p. 54 f.).

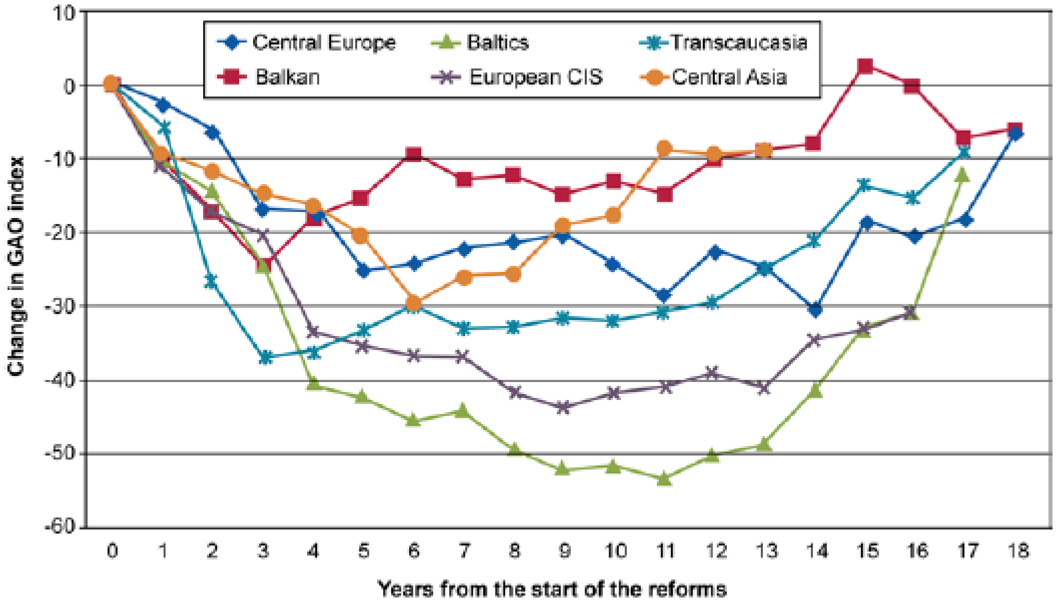
The highest land productivity shows Japan. Medium-sized land productivity can be found in Asia, Eastern and Western Europe, and North America. Land productivity is lowest inSub-Sahara Africa and Australia and New Zealand. Over the four and a half decades all regions and countries could increase their land productivity. But global land productivity growth has been substantially slower since 1990 (Alston et al. 2009). Additionally, the throwback in Eastern Europe and the Former Soviet Union is clearly visible (see Box 1).

Box 1

Agricultural production and productivity in the former Soviet Union and Central and Eastern Europe

Economic and institutional reforms have dramatically affected the agricultural performance in all Central and Eastern European countries and Former Soviet Union republics. Not only did agricultural output fall dramatically in the region but also efficiency decreased during the transition. In the early transition period, gross agricultural output decreased in all regions by at least 20%. The transition from a centrally planned economy to a market-orientated economy coincided in all countries with subsidy cuts and price liberalization, which in general caused input prices to increase and output prices to decrease. Purchased inputs were no longer affordable at the new relative prices, and the decrease in input use caused a decrease in agricultural output. In the Baltic states and the European CIS, output decreased to about 50% to 60% of the pre-reform output (Figure 2). In Central Europe and Central Asia, output declined by 25% to 30%. Output stabilized in the mid-1990s in Central Europe and later also in the other regions. Currently, agricultural output is close to the pre-reform output level in most countries (Swinnen et al. 2010).

Figure 2: Development of gross agricultural output in former Soviet Union and Central and Eastern Europe



Note: Reforms started in 1989 (=year 0) in Central Europe and the Balkan countries and in 1990 (=year 0) in the Baltic states, the European CIS, Transcaucasia, and Central Asia.

Source: Swinnen et al. (2010), p.281

The regions and country groups reveal large differences in labour productivity. In 2005, low-income countries as a group averaged just $ 331 of output per agricultural worker, compared with $ 1,032 per worker for middle-income countries and $ 26,975 per worker for high-income countries. Therewith, labour productivity is clearly tied to the overall per capita income of countries. It should kept in mind that broad regional productivity trends mask significant local variation caused by a host of agro-ecological, market-related, and policy-related factors (Alston et al. 2010, p. 55).

Development of productivity in the European Union

Crop production in the EU shows a high diversity in land productivity, between and inside Member States. Level of productivity is dependent from

- agro-ecological conditions,
- farm economics and
- regional economic framing conditions.

Information on the intensity of land use in the EU is available based on the output in economic terms of agricultural products per hectare. Therewith, different types of output from crop and animal production are integrated (Andersen et al. 2007; Kempen et al. 2011). Three levels of intensity are distinguished (Andersen et al. 2007):

- Low intensity: Total value of agricultural products per ha < 500 Euro,
- Medium intensity: Total value of agricultural products per ha ≥ 500 and < 3,000 Euro,
- High intensity: Total value of agricultural products per ha ≥ 3,000 Euro.

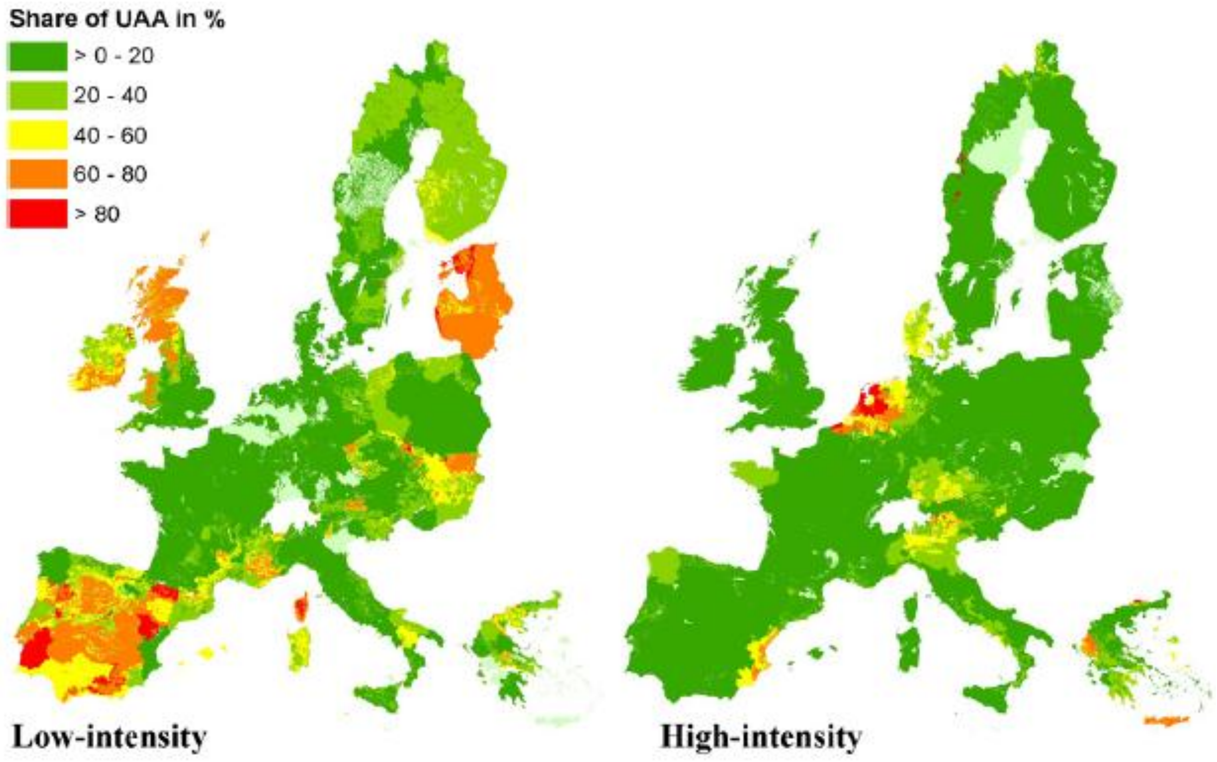
Clusters of high intensity farming exist in the Netherlands and the bordering regions of Germany and Belgium and in the Eastern part of Spain (figure 3). Higher proportions of high intensity farms can be found also in Denmark and in some regions of Greece and Italy. High intensity is associated with regions of concentrated livestock farming, horticulture, permanent crops and intensive crop production. Low intensity farming follows a more scattered pattern across the EU. Three larger clusters are found on the Iberian Peninsula, in Northern parts of United Kingdom and in Ireland, an in the Baltic States. Permanent grassland, sheep and goat production, and mixed farming are important activities (Andersen et al. 2007; Kempen et al. 2011). Part low intensity area is classified as High Nature Value (HNV) farmland (EEA 2009, p. 18). In the EU-15, a quarter of the agricultural area is managed by low intensity farms, and nearly 15% by high intensity farms (Table 4).

Table 4: Share of farms, area, livestock units (LU) and output covered by different levels of farming intensity in EU-15, 2003 (in %)

Level of farming intensity	Share of farms	Share of area	Share of LU	Share of outcome
Low intensity	11.8	23.6	6.2	2.9
Medium intensity	53.4	61.6	39.0	37.9
High intensity	34.8	14.8	54.9	59.2

Source: Andersen et al. (2006), p.19

Figure 3: **Distribution of low-intensity and high-intensity farm types on agri-environmental zones in the EU**



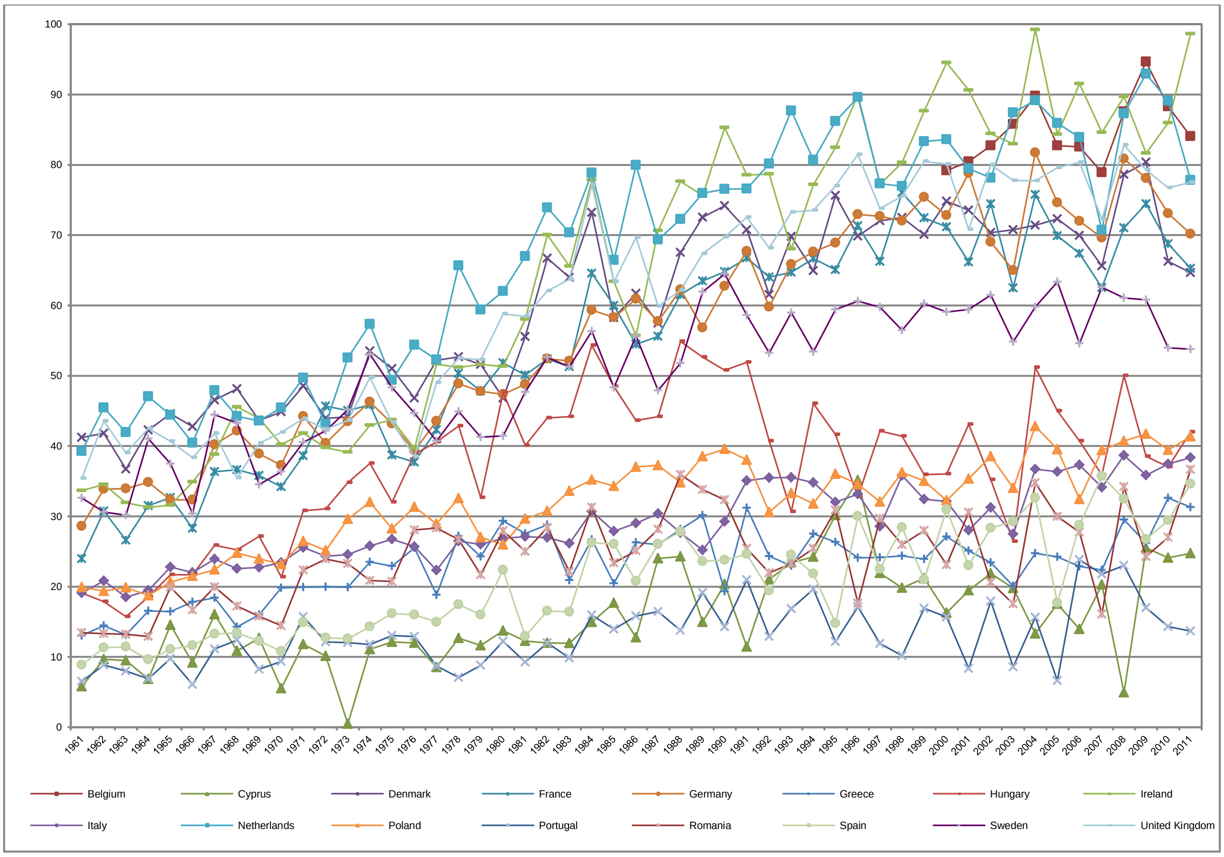
Legend: Bulgaria, Cyprus, Malta and Romania not included. The distribution of medium intensity farm types is not included. The lightest green indicates regions where the farm type in question is not present.

Source: Kempen et al. (2011)

Average yields in cereal production show remarkable differences in the EU. Highest levels are achieved in North-western Europe. Yields in Southern and Eastern Europe are much lower. Average yields of eight to ten tonnes per ha are achieved in favoured arable regions of the United Kingdom, Denmark, Germany or France and yields as low as two to three tonnes per ha in the dry interior of the Iberian peninsula and in some other Mediterranean countries. Exemption is maize where Greece and Spain belong to the leading countries due to the favourable climatic conditions (see Annex A). In the United Kingdom, the yields of major crops increased from the 1950s to the 1990s with a growth rate about 2% per year. After the 1990s, growth rates falls to about 0.2% per year, as before the World War II (Piesse, Thirtle 2010, p. 154-155). Similar developments took place in countries with intensive wheat production such as Belgium, Denmark, France, Germany and the Netherlands (Figure 4). For the UK, the reason for this reversal are seen in the decline of public research & development expenditures, their targeting away from productivity enhancement and the demise of public extension service (Piesse, Thirtle 2010, p. 179-184).

In contrast to land productivity, labour productivity continued to increase over the last years in the United Kingdom (Piesse, Thirtle 2010, p. 161), and in other industrialized countries. Over the last decades, labour productivity growth rates were higher than land productivity growth rates in Western European countries and in North America (Figure 1).

Figure 4: Development of wheat yields in selected European countries, 1961-2011 (in 100kg/ha)



Source: FAOSTAT, online database, accessed April 2013

2.3. Farming structures

Farming at the global level

Worldwide, the vast majority of farmers are *small-scale farmers*, also called smallholders or family farmers. Estimated 85% of the farmers countries produce on less than 2 hectares (World Bank 2007, p. 90; von Braun, Diaz-Bonilla 2008, p. 7). In countries as diverse as China, Egypt and Malawi, 95% of the farms are smaller than 2 hectares (FAO 2010c). The dominance of smallholders is found mostly in countries of East, South-East and South Asia, and Sub-Sahara Africa (Table 5). Some increase of the average farm size can be seen from the equator to the more arid areas in the direction of the tropics. Countries with high percentage of irrigated land show a low average farm size. These relationships reflect land productivity (Meyer 2011). Average farm size is much higher in countries with greater percentages of permanent grassland. In the last decades, many developing countries saw a *decline in farm size* and in land/labour ratios (Chapter 2.2), i.e. the ratio of cultivated land to agricultural population (Hazell et al. 2010; Jayne et al. 2010). Missing labour opportunities outside agriculture are seen as a major cause for this development.

Small-scale farms play also an essential role in countries with a higher average farm size such as Brazil, Venezuela or Tunisia. A fifth or more of all farms in these countries are smallholders, constituting a high number of farm households. Part of developing countries has severe land inequalities between smallholder and large-scale farms, e.g. in Latin America and South Africa. Stronger unequal distribution of farm size is characterised by higher Gini coefficients (Table 5). Partly, there are also major disparities in land distribution within the small-scale farm sector itself. In selected Eastern and South Africa countries, households in the highest per capita land quartile control between 5 and 15 times more land than households in the lowest quartile (Jayne et al. 2010).

Small-scale farmers can be found under more or less all *agro-ecological and socio-economic conditions*. From the agro-ecological point of view, smallholders are located in irrigated and rain-fed areas, and in high-productive and marginal farming areas. Smallholders produce partly with extensive use of external inputs such as synthetic fertilizers and pesticides, and partly without external inputs (Meyer 2011). Even today more than 80% of African farmers and 40 to 60% of those in Asia and Latin America still work with strictly manual tools (Mazoyer, Roudat 2006, p. 442).

Table 5: Average farm size and dispersion measures in different regions, 1990s

Region	Mean size (ha)	Size < 2 ha (%)	Gini coefficient	Permanent pasture (%)
Sub-Sahara Africa	2.4	69.2	0.49	9.0
West Asia + North Africa	4.9	65.0	0.70	7.1
South Asia	1.4	77.8	0.54	-
Southeast Asia	1.8	57.1	0.60	1.4
East Asia	1.0	92.2	0.50	-
Central America + the Caribbean	10.7	62.8	0.75	38.0
South America	111.6	35.7	0.90	74.6
United States	178.4	4.2	0.78	47.9
Europe	32.3	29.9	0.60	35.9

Source: Based on Eastwood et al. (2010), p. 3330

The *market integration of small-scale farmers* is very different (Bennett, Franzel 2009, p. vii):

- Subsistence: Farmers hardly participate in markets at all;
- Transitional integration: Farmers sell some of their products, generally in informal, local markets;
- Cash-cropping: Farmers sell nearly their entire crop, generally through formal markets.

The surplus production and marketing (of staples) is concentrated on relative few small-scale farmers (Barrett 2008; Jayne et al. 2010). Overall, a considerable amount of the food supply of farm households comes in developing and emerging countries from their own food production.

In most countries, both rich and poor, the average farm size is quite small, with generally owner-operated farms. The main reason is that agricultural production has few technical economics of scale, implying that a range of production forms can coexist. In contrast, processing and distribution are characterized by significant economics of scale from which results often high levels of concentration (Deninger et al. 2011, p. 28).

Following World War II, the number of farms has decreased and the average farm size increased in industrialized countries, based on technological development. Mechanization increased the labour productivity (Chapter 2.2). Tractors had essentially replaced animal power, and mechanical harvesting of crops became routine by the late 1960s. Advances in plant breeding and inexpensive chemical fertilizers and pesticides had enabled high growth rates in agricultural productivity (Dimitri et al. 2005). Farm size increased parallel to rising wages in the non-agricultural sector, suggesting that the desire to obtain an income comparable to non-agricultural income was a main driving force in farm size change (Deininger et al. 2011, p. 30).

At the upper end of the farm size scale, very large corporate farms – so called "megafarms" – exist in some land-abundant developing and transition countries, with up to 1 million hectare and operational units that often exceed 10,000 ha. Vertical integration with processing, marketing, and export logistics is common (Deininger, Byerlee 2012). Large-scale production can be found in "plantation crops" (e.g. palm oil, sugar cane) and can be the result of specific transformations processes such as in Russia, Ukraine and Kazakhstan.

Since the global food crisis 2007-08, foreign direct investments in land have increased dramatically. Of the approximately 1,000 international land deals (many of which are implemented with national partners) recorded as of May 2012, 46% targeted land in Sub-Saharan Africa and 37% land in Asia. The majority of international land deals to date have occurred in those countries that experience higher levels of hunger and where the population and national incomes depend heavily on agriculture: 32 countries where agriculture accounts for a higher share of GDP (more than 5 percent) and hunger is serious or alarming (a GHI score of more than 10) received investments affecting about 41 million hectares, accounting for 73% of the total investment. In 7 countries, land deals account for more than10% of total agricultural area: Cambodia, Ethiopia, Indonesia, Lao PDR, Liberia, the Philippines, and Sierra Leone (IFPRI et al. 2012, p. 29). Land acquisitions in Africa in 2009 alone amounted to 39.7 million ha – greater than the total agricultural land in Belgium, Demark, France, Germany, the Netherlands, and Switzerland combined (Deiniger et al. 2011). A country's probability to be targeted by large scale farmland investment is positively associated with weak land governance and failure to protect traditional land rights (Deiniger, Byerlee 2012).

Farming in the European Union

The farm structure in the EU Member States varies remarkably. The Agricultural Survey 2010 (Farm Structure Survey - FSS) accounts for close to 12 million farms in the EU-27. These farms covered around 170 million hectares of utilised agricultural area (UAA), slightly over 40% of the EU-27 territory. The number of farms decreased from 1980 (EU-9) respectively from1990 (EU-12) to 2010 considerably[22] (see Annex A). The holdings from only three Member States, Romania (32%), Italy (14%) and Poland (13%), made up for nearly 60% of the total number of EU-27 holdings (Figure 5) (EUROSTAT 2012a, p. 27).

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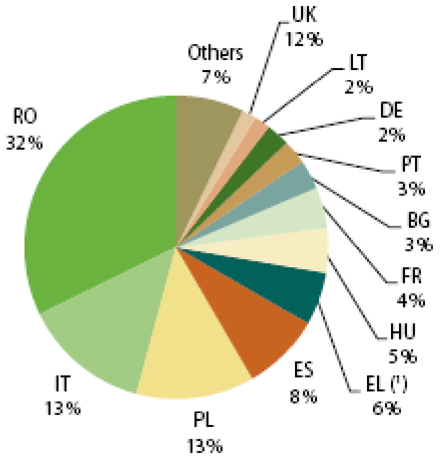
[22] Number of agricultural holdings in EU Member States, 1966-2010: Table A1 in Annex A

Figure 5: Percentage of number of agricultural holdings by EU Member States (EU-27) in 2010



(¹) BE, EL, LU, UK: provisional data

Source: EUROSTAT (2012a), p. 27

Of the total EU-27 holdings, 49% had less than 2 hectares[23]. These small-scale farms represent only 2% of the total UAA (EUROSTAT 2012a, p. 27), but the holdings with a total standard gross margin (SGM) under 1 European Size Unit (1,200 €) account for 39% of the regular farm workers and 23% of the total farm work (AWU) in FSS 2007 (Box 2.2). In 7 Member States (Romania, Latvia, Lithuania, Austria, Malta, United Kingdom and Poland), the percentage of UAA covered by the small-scale farms is higher than 10% (EUROSTAT 2012b).

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[23] Distribution of utilized agricultural area by size of the farm: Figure A71 in Annex A

Box 2

Subsistence and semi-subsistence farming in the European Union

Semi-subsistence farms are defined as "agricultural holdings which produce primarily for their own consumption and also market a proportion of their output" in the Council Regulation on Support for Rural Development by the European Agricultural Fund for Rural Development (EC No. 1698/2005). Subsistence and semi-subsistence farming in the EU has seen a massive expansion after the Eastern enlargements.

There are 16 Member States in which farms allocating more than 50% of the output for household consumption are of any importance – the twelve New Member States (NMS-12), Greece, Italy, Portugal and Spain. 40% of these farmers are 65 years of age or older (the share of older farmers is particularly high in Greece, Italy, Portugal, Spain and Bulgaria) (Davidova 2011). In the NMS-12, semi-subsistence farms are not only the predominant farm structure but they use also a large share of factors and provide regular labour for more than 9 million people (Table 6).Romania stands out from the rest of the countries: semi-subsistence and subsistence farms represent almost one third of the SGM of Romanian agriculture (FSS 2007, EUROSTAT 2012b). Location in less favoured areas (LFAs) is more typical for the small holdings in the EU-15than in the NMS (Davidova 2011).

The problems of semi-subsistence farms are low cash incomes and incidence of poverty, sub-optimal use of land and labour, a lack of capital and poor contribution to rural growth. Frequently, these semi-subsistence farms are run by older farmers with low levels of general and agricultural education, possessing only practical skills in farming and generally being non-innovative. However, they play an important welfare function in some rural areas in Europe; and they are important providers of environmental benefits and contributors to cultural landscape (Davidova 2011).

Table 6: Importance of semi-subsistence farming (with more than 50% of output self-consumed) in the EU-27, 2007

	Absolute figures (1,000)			Share in total (%)		
	NMS-12	EU-15	EU-27	NMS-12	EU-15	EU-27
Number of holdings	5,300	610	5,910	65.9	10.8	43.1
UAA (ha)	10,322	1,196	11,528	21.6	0.9	7.6
Regular labour (AWU)	2,823	263	3,086	49.2	5.2	28.6
Regular labour (persons)	9,242	1,072	10,314	60.8	9.3	38.7
Total LSU	6,382	397	6,779	24.3	0.4	5.0
Total SGM	3,935	2,102	6,037	20.1	1.6	3.9

Legend: UAA – Utilised Agricultural Area, LSU – Livestock Units, SGM – Standard Gross Margin, NMS – New Member States

Source: Based on Davidova (2011)

A UAA of at least 100 hectares had 325,000 holdings, 3% of the total EU-27 holdings[24]. This group of largest holdings had 50% of share of the total EU-27 UAA (EUROSTAT 2012a, p. 27, see Annex A). In Bulgaria, the Czech Republic, Hungary, Estonia and Slovakia, the larger farms occupying 20 % of the UAA are all above 1000 ha. This pattern occurs in several of the new Member States; here the structure of the agricultural holdings is related to the particular ownership structure made up of large-scale corporate farms inherited from former state-owned cooperatives. Within the old Member States (EU-15), Greece, with an average area of 64 ha for the larger farms, has the lowest average area while the United Kingdom is the only country showing an average area over 2,000 ha for the group of larger farms. This can be explained for the United Kingdom by the fact that larger farms specialize in grazing livestock extensively. The larger farms do not have such a high average UAA per farm in the countries where they represent a greater percentage. On the other hand, with the exception of Italy, Cyprus and Poland, in countries where the number of larger farms is less than 1 % of all farms, the average UAA per large farm is over 500 ha (EUROSTAT 2013e).

In 21 countries the smaller farms have a higher SGM/ha than the larger farms[25]. In nine of those countries (Bulgaria, Greece, Spain, Italy, the Netherlands, Austria, Portugal, Romania and the United Kingdom) the SGM/ha of the smaller farms is more than twice the SGM/ha of the larger farms. In the Czech Republic, Estonia, Ireland, Latvia, Lithuania, Slovakia and Sweden, the larger farms' SGM/ha is slightly higher than the SGM/ha of the smaller farms (EUROSTAT 2013e).

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[24] Distribution of utilized agricultural area (UAA) by UAA size of the farm: Figure A71 + A72 in Annex A

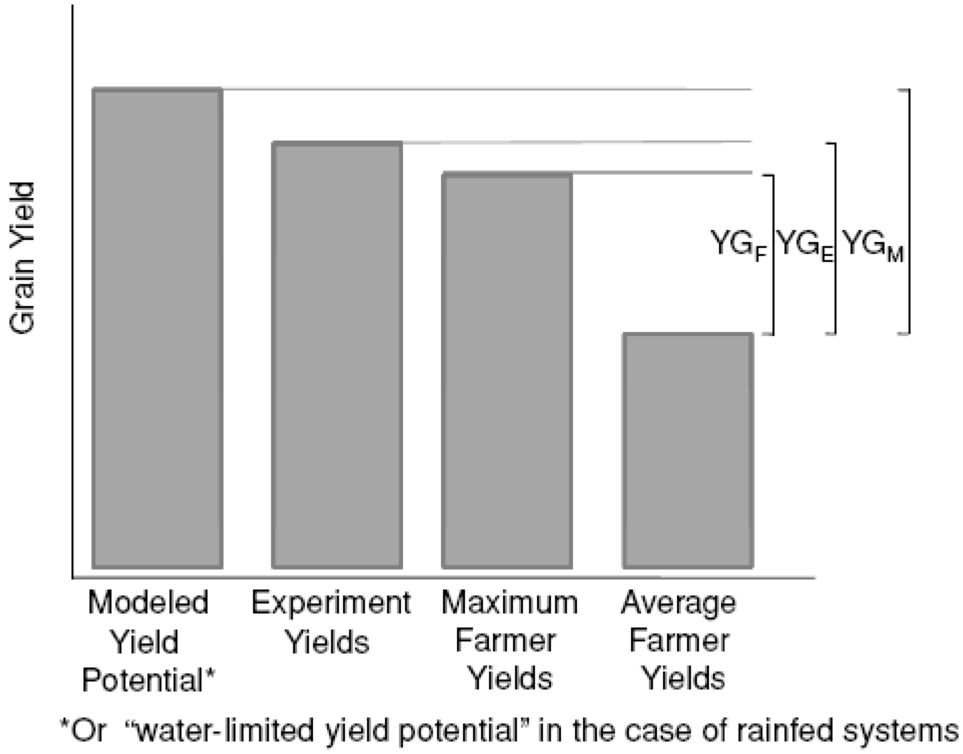
[25] Stand gross margin of smaller and larger farms per farm and per hectare: Table A2 in Annex A

3. CONSTRAINTS IN CROP PRODUCTION

3.1. Yield gap and objectives of sustainable intensification

Yield gaps are estimated by the difference between yield potential and average farmers' yields, for a specified spatial and temporal scale of interest. The measurement of yield gaps rests on the definition and measurement of yield potential which is an idealised state of crop development without any biophysical limitations other than uncontrollable factors, such as solar radiation, air temperature, and rainfall in rainfed systems. Therefore, to achieve yield potential requires optimal management of all yield-restricting production factors (such as seed date, plant population, nutrients supply, protection against pest, disease and weed competition). Yield potential and associated yield gaps can be assessed by three main techniques: model simulations, field experiments and maximum farmer yields (Figure 6). Each approach has its own strengths and weaknesses. Estimates of yield potential can often differ by 50% or more, with estimation especially difficult for rainfed conditions (Lobell et al. 2009).

Figure 6: Conceptual framework for three measures of yield potential and average farmer yields



Note: Different measures of the yield gap(YG) are indicated at the right side of the figure: YGM,model-based yield gap (yield potential is simulated with a model); YGE,experiment-based yield gap (yield potential is estimated with a fieldexperiment); and YGF, farmer-based yield gap (yield potential is estimated withmaximum of farmers' yields).

Source: Lobell et al. (2009), p. 185

Yield gaps assessed around the world show a wide range, with average yields ranging from roughly 20% to 80% of yield potential. Many irrigated cropping systems have yields at or approaching 80% of yield potential. Many rainfed cropping systems, in contrast, appear to have relatively large yield gaps. Additionally, performance of farmers within a small region shows often a remarkable heterogeneity, with yields spanning at least a factor of two (Lobell et al. 2009).

Based on climatic potential yields, developed countries show in many cases low yield gaps. This is especially true for maize, wheat, potato, rapeseed, rye and sunflower in Western Europe, as well as maize and soybean in the United States. Higher yield gaps occur more often in Southern European countries like Spain, Portugal and Italy. The low yield gaps of Western Europe often come to an abrupt halt at the border with Eastern Europe. The yield gaps for most crops, including maize, wheat, barley, rapeseed and sunflower, are quite high in Eastern Europe (Licker et al. 2010).

Yield gaps to the climatic potential yields tend to be more variable in Asia. Clusters of low yield gaps exist in and around the more populous provinces of China (e.g., for rice, wheat, millet, potato, rye) and in some parts of the Indio-Gangetic Basin (e.g., for rice, wheat, rapeseed). Yield gaps in Africa are on the higher end of the spectrum for many crops, especially maize and wheat. Cassava and pulses have generally low yield gaps throughout much of the continent (Licker et al. 2010).

Causes for yield gaps vary by crop and global region. For example, Eastern Europe and West Africa stand out as hotspots of nutrient limitation for maize, whereas Eastern Europe seems to experience nutrient limitation for wheat. Co-limitation of nutrients and water is observed across East Africa and Western India for maize, the Mediterranean for wheat, and in Southeast Asia for rice (Mueller et al. 2012).

Another spatial differentiated analysis works with stochastic frontier production function which represents the maximum attainable output for a given set of inputs and calculates the efficiencies of agricultural production. The calculated yield gaps and efficiencies of wheat, maize, and rice production show that the actual grain yield in some regions is already approximating its maximum possible yields while other regions show large yield gaps and therefore tentative larger potential for intensification (Neumann et al. 2010). For example, potential maize yields for Europe show a gradient from the North-East of Europe to the South-West. The results from the frontier yield analysis are confirmed by a recent study on simulated water-limited potential maize yields for Europe (Reidsma et al. 2009), although the gradient is stronger and the potential yields tend to be lower in this study.

Independent of the correct measurement of yield gaps, it is broadly recognised that many global regions show large yield gaps. Therefore, it makes sense to explore the potential for increasing production from already cultivated land and existing cultivars, independent from progress in plant breeding. An unique approach is not possible because the factors explaining inefficiencies in production widely vary by region, and are related to complex social, economic, and political processes (Neumann et al. 2010).

3.2. Constraints in crop production

An understanding of major constraints in the agricultural crop production is needed as a starting point for the identification of options for sustainable intensification. Important constraints are (IAASTD 2009, Royal Society 2009):

- Soil fertility
- Water availability
- Crop nutrition
- Pests, diseases and weed competition
- Demand for energy input

It has to be taken into account, that constraints on food crop production differ widely across regions.

3.2.1. Soil fertility

Soil is defined as the top layer of the earth’s crust and is composed of mineral particles, water, air and organic matter, including living organisms. It is a complex, mutable, living resource which provides many ecosystem services: food and other biomass production, storage, filtration and transformation of substances including water, carbon and nitrogen (Louwagie et al. 2009, p. V). Soil is a non-renewable (at least over non-geological timescales) resource (Royal Society 2009, p. 13). Key functions of processes in soil ecosystems are primarily about regulating the three major bio-geochemical cycles on earth: nutrient, carbon and water cycling (Dias, Coates 2012). Good soils are not evenly distributed around the world. Depending on parent material, climate, relief, vegetation, and time that determine soil formation; soils have inherent constraints that limit their productivity.

Soil quality reflects properties of a soil such as fertility (crop nutrients, soil organic matter content), drainage and water holding capacity, ease of cultivation (physical structure, soil organic matter content), freedom of contaminants, soil flora and fauna (Royal Society 2009, p. 13). Soil quality integrates different soil state variables and functions in order to assess the sustainability of land-use practices. Soil fertility (“Bodenfruchtbarkeit” in German-language literature) is partly used as a term to describe the yield-giving capacity (Patzel et al. 2000).The management of soil fertility is essential to enhancing and sustaining agronomic and biomass productivity (Pretty et al. 2010).

Based on Liebig’s “mineral nutrition theory” and breakthroughs in the processes of fertilizer industry, the development of modern (industrialized) agriculture was stirred by intensive mineral fertilization as a substitute for organic practices. Although understanding of soil organic matter (SOM) and soil biological functioning was improving it had little impact on the rise of new mineral-based cropping patterns. SOM is understood today as the non-living product of the decomposition of plant and animal substances. SOM tightly controls many soil properties and major biogeochemical cycles so that its status is often taken as a strong indicator of fertility and land degradation (Manlay et al. 2007).

Soils can undergo a series of degradation processes: water erosion, wind erosion, decline of soil organic matter, compaction, salinisation (and sodification), contamination, and declining soil biodiversity. Processes of soil degradation are dependent from regional and local vulnerability of soils and often caused by land use change and agricultural land use practices. This can have serious consequences for crop productivity.

Estimates of the extent of land and soil degradation are varied (Stringer 2012). In the 1990s, GLASOD (the Global Assessment of Human-Induced Soil Degradation) provided a global map of soil degradation at a 1:10,000,000 scale (Oldeman et al. 1991), based largely on (somewhat subjective) expert opinions on the type, extent, degree, rate and causes of degradation. GLASOD considered four main causes: agriculture; deforestation; overgrazing; and industrial pollution; and assessed 3.5 billion ha of degraded soil globally.

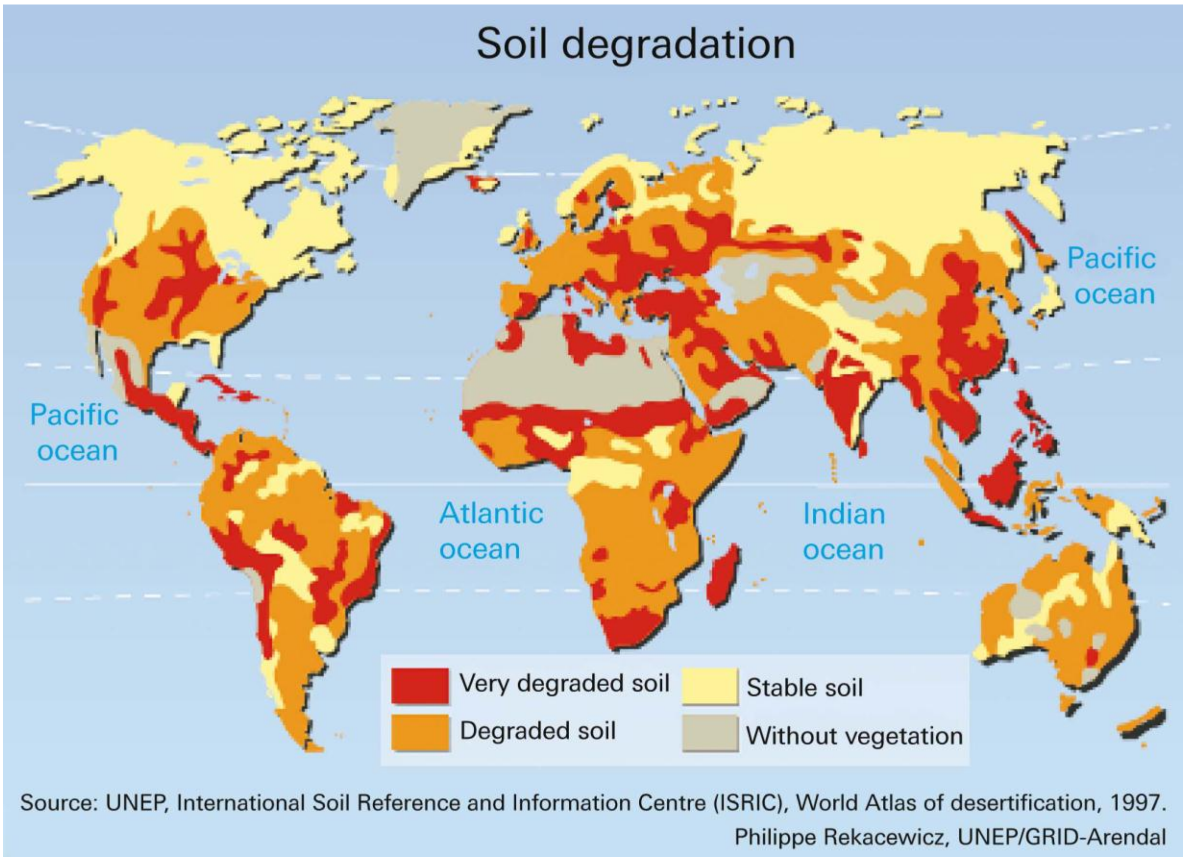
LADA (Land Degradation Assessment in Drylands) and GLADA (Global Assessment of Land Degradation and Improvement) represent more recent assessment efforts. These follow on from GLASOD across global, national and sub-national scales to identify the status and trends of land degradation in drylands, degradation hotspots and bright spots (both actual and potential) and find that 24% of the global land area has been degrading over the past 25 years. This contrasts with the 15% of degraded soil (not land) identified in GLASOD (Stringer 2012).

More recently, within the Millennium Ecosystem Assessment (MEA 2005), land and soil issues are considered through an ecosystem approach, which focuses on the status and trends of the ecosystem services that land and soil provide. The assessment concludes that >60% of ecosystem services have been degraded. However, it provides limited information on the specific status of soil. It nevertheless gives particular consideration to desertification. Drylands cover 41% of the planet’s land area and are inhabited by more than 2 billion people (Middleton et al. 2011). The MA suggests with medium certainty that 10-20% of drylands are already degraded, with a much larger area under threat from desertification in the future.

Arecent relevant initiative is GlobalSoilMap.net, a consortium that aims to make a new digital soil map of the world, predicting soil properties at fine resolution (Sanchez et al. 2009). Soil degradation (see

Figure 3.2) is of paramount importance and all present and future crop production depends upon the maintenance and improvement of soil quality (Royal Society 2009, p. 13).

Figure 7: Global soil degradation



Source: Royal Society (2009), p. 14

Main threats to soil fertility in Europe[26] are (Jones et al. 2012):

> *Soil erosion by water*: This is one of the most widespread forms of soil degradation in Europe. 105 million ha (or 16% of Europe's total land area, excluding Russia) were estimated to be affected by water erosion in the 1990s. The Mediterranean region is particularly prone to water erosion because it is subject to long dry periods followed by heavy bursts of intense rainfall on steep slopes with fragile soils. No harmonised measures of actual soil erosion rates exist for Europe. A recent new model of soil erosion by water constructed by the JRC has estimated the surface area affected in the EU-27 at 130 million ha. Almost 20% is subjected to soil loses in excess of 10 t/ha/year (Jones et al. 2012, p. 4, 15).

> *Soil erosion by wind*: Estimates range from 10 to 42 million ha of Europe's total land area. Wind erosion is a serious problem in many parts of northern Germany, eastern Netherlands, eastern England and the Iberian Peninsula (Jones et al. 2012, p.17).

> *Compaction*: Soil compaction is a form of physical degradation under pressure and can be induced by the use of heavy machinery in agriculture. Estimates of areas at risk vary. Some researchers classify

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[26] Maps on regional European soil erosion risk, organic carbon content of topsoil, susceptibility to soil compaction: Figures B1-B3 in Annex B

around 36% of European subsoils as having high or very high susceptibility to compaction. Other sources estimate 33 million ha (or 4% of the European land surface) being affected in total (Jones et al. 2012, p. 4, 18).

> *Soil organic matter*: Around 45% of the mineral soils in Europe have low or very low organic carbon content (0 – 2%) and 45% have a medium content (2 – 6%) (Rusco et al 2001). Low levels are particularly evident in southern European countries, but can be found almost everywhere, including some parts of Belgium, France, Germany and the United Kingdom. Except for the rapid removal of soil organic content (SOC) by erosion and landslides, decreases in SOC levels as a result of intensification of agriculture, deforestation or conversion of grassland to arable land are slow processes. Some recent studies suggest that SOC in European arable land is decreasing (Heikkinen et al. 2013; Meersmans et al. 2011; Saby et al. 2008; Vleeshouwers, Verhagen 2002). SOC decline is of particular concern in the Mediterranean region, where high temperatures and droughts can accelerate its decomposition (Jones et al. 2012, p. 13).

> *Desertification*: Prolonged droughts and more irregular precipitation, combined with unsustainable use of water and agricultural practices, could lead to desertification. The situation is most serious in southern Portugal, much of Spain, Sicily, south-eastern Greece and the areas bordering the Black Sea in Bulgaria and Romania. In southern, central and eastern Europe, 8% of the area or 14 million ha show very high or high sensitivity to desertification (Jones et al. 2012, p. 27-28)

3.2.2. Water availability

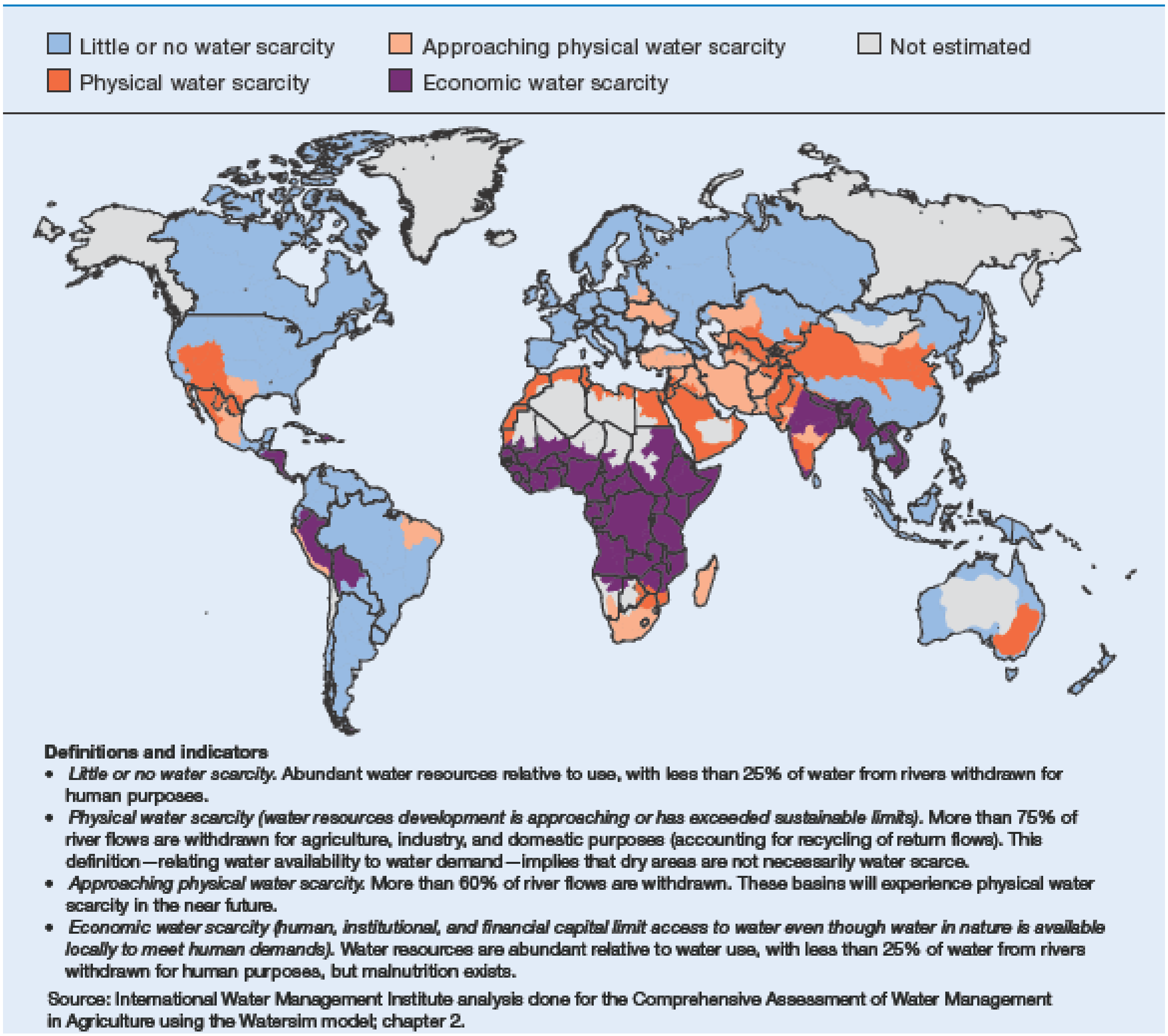
Water is essential for plant growth. Water stress can have major impacts on productivity andyield depending on timing, severity, and duration (Steduto et al. 2009). Water constraints on agriculture increase from the Equator towards the Tropics, in accordance with the planetary circulation and the associated precipitation events (Butz 2011).

Irrigated agriculture is the dominant user of water, accounting for about 80% of global water use from rivers, lakes and groundwater, so called 'blue water'. Irrigated farming accounts for only 19% of agricultural land, but it produces about 40% of the world's food (Hanjra, Qureshi 2010). In the last five decades, irrigated land has doubled and strongly contributed to increasing agricultural production. Water resources and irrigation are distributed with huge variations across and within countries. In Sub-Saharan Africa, only 4% of the area in production is under irrigation, compared with 39% in South Asia and 29% in East Asia (World Bank 2007, p. 9; UNESCO 2006, p. 22).

55% of the gross value of our food is produced under rainfed conditions on nearly 72% of the world's harvested cropland (Molden 2007, p. 15). Around the year 2000, green water contributed estimated 87% of the total consumptive water use in croplands worldwide (Liu, Yang 2010). Important opportunities are seen in upgrading rainfed agriculture through better water management practices. Better soil and land management practices can increase water productivity, adding a component of irrigation water through smaller scale interventions such as rainwater harvesting. Integrating livestock in a balanced way to increase the productivity of livestock water is important in rainfed areas (Molden 2007, p. 15).

Water scarcity, defined in terms of access to water, is a critical constraint to agriculture in many areas of the world (Figure 8). A fifth of the world's people, more than 1.2 billion, live in areas of physical water scarcity, lacking enough water for everyone's demands. About 1.6 billion people live in water-scarce basins, where human capacity or financial resources are likely to be insufficient to develop adequate water resources. Behind today's water scarcity lie factors likely to multiply and gain in complexity over the coming years. A growing population is a major factor, but the main reasons for water problems lie elsewhere: lack of commitment to water and poverty, insufficient and inadequately targeted investment, insufficient human capacity, ineffective institutions and poor governance (Molden 2007; STOA 2009, p. 56).

Figure 8: Areas of physical and economic water scarcity



Definitions and indicators

- *Little or no water scarcity.* Abundant water resources relative to use, with less than 25% of water from rivers withdrawn for human purposes.
- *Physical water scarcity (water resources development is approaching or has exceeded sustainable limits).* More than 75% of river flows are withdrawn for agriculture, industry, and domestic purposes (accounting for recycling of return flows). This definition—relating water availability to water demand—implies that dry areas are not necessarily water scarce.
- *Approaching physical water scarcity.* More than 60% of river flows are withdrawn. These basins will experience physical water scarcity in the near future.
- *Economic water scarcity (human, institutional, and financial capital limit access to water even though water in nature is available locally to meet human demands).* Water resources are abundant relative to water use, with less than 25% of water from rivers withdrawn for human purposes, but malnutrition exists.

Source: International Water Management Institute analysis done for the Comprehensive Assessment of Water Management in Agriculture using the Watersim model; chapter 2.

Source: Molden (2007), p. 11

Poor water management can lead to land degradation in irrigated areas through salinisation and waterlogging. Nearly 40% of irrigated land in dry areas of Asia is regarded to be affected by salinisation. The consequences are declining productivity and loss of agricultural land (World Bank 2007, p. 183; STOA 2009, p. 55).

Continued increase in demand for water by non-agricultural uses, such as urban and industrial uses and greater concerns for environmental quality have put irrigation water demand under greater scrutiny. Continued increase in demand for irrigation water over many years has led to changed water flows, land clearing and therefore deteriorated stream water quality (Hanjra, Qureshi 2010).

Growing demand for food must be met against a backdrop of rising global temperatures, and changing patterns of precipitation (Foresight 2011). Climate change may affect agriculture and food security by altering the spatial and temporal distribution of rainfall, and the availability of water, land, capital, biodiversity and terrestrial resources. The impacts of climate change on global food production are small but geographically very unevenly distributed, with losses felt mostly in arid and sub-humid tropics in Africa and South Asia and particularly in poor countries with low capacity for adaptation (Hanjra, Qureshi 2010). For these reasons, increasing the productivity of both 'green' and 'blue' water use is required. The need for improved crop, soil and water management practices, particularly in light of climate change, is growing (Pretty et al. 2010).

In Europe, many countries have experienced drought episodes of various significance (ranging from less to more severe), duration (a few month to years) and extend (local to regional to national) in the past 40 years[27]. From the decade 1971-1980 to 2001-2011, the number of countries affected by drought per decade has increased from 15 to 28 and had also reached North and Eastern EU (Kossida et al. 2012, p. 18). Recently, western and south-western Europe was affected by severe summer and spring droughts in 2011 and 2012 (EEA 2012, p. 38).

From the total number of groundwater bodies reported in the Water Framework Directive (WFD) River Basin Management Plans (RBMPs), 6.37 % (782 out of12 268 classified groundwater bodies) were classified as being in poor quantitative status in 2009[28]. These are distributed throughout several countries, namely Spain, the United Kingdom, Belgium, the Czech Republic, Denmark, Italy and Malta. Those countries all have groundwater quantitative problems, but these problems are mainly found in specific River basin districts and not in the whole country. The exception to this is Cyprus, where approximately 70 % of its groundwater bodies hold poor status (EEA 2012, p. 37).

The percentage of river basin area in the EU under water stress is estimated to be around 10% year around and 23% for the summer period. Southern European basins are more likely to experience water scarcity during the summer months[29]. This is the case for Spain, Italy and Greece for which peak agriculture and tourism water demands take place during the summer when the natural water resource available is at its lowest (Strosser et al. 2012).

3.2.3. Crop nutrition

Nitrogen (nitrate or ammonium), phosphorus (phosphate) and potassium are the major crop nutrient, and are crucial determinants of crop yields. Agricultural productivity growth and higher yields are dependent from inputs as fertilisers. Input requirements depend largely on the applied agricultural production systems.

There is widespread nitrogen and phosphate deficiency in crop production which means that the potential yield of crop genotypes is not reached. This deficiency is particularly acute in the developing world where nutrient inputs are completely inadequate because they are unaffordable or unavailable (Royal Society 2009, p. 16). Smallholders have removed large quantities of nutrients from their soils without applying sufficient quantities of manure or fertiliser to replenish the soil. This has resulted in a very high average annual depletion rate: 22 kilograms of nitrogen, 2.5 kilograms of phosphorus and 15 kilograms of potassium per hectare of cultivated land over the last 30 years in 37 African countries – an annual loss equivalent to $4 billion in inorganic fertiliser (InterAcademy Council 2004, p. 47).

But highly heterogeneous farming systems (especially in Sub-Sahara Africa), the diversity among agro-ecological systems, and in soil nutrient management, restricts the scope of global estimations of nutrient balances which depend on data sources such as FAO production statistics and the world soil map. There is evidence of farmers' achievements in terms of sustained production, and investments in soil fertility maintenance at local level, depending from macro-economic policies and demand-side factors (Giller et al. 2011; Mortimore, Harris 2005).

In many soils, applied inorganic phosphate rapidly becomes inaccessible to plants due to its adsorption to soil mineral particles and occlusion in association with iron or aluminium oxides. In situations where available phosphate levels are low, mycorrhizal associations are critically important and phosphate deficiency is the primary constraint on yield (Royal Society 2009, p. 16).

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[27] Map of European countries with observed drought periods: Figure B4 in Annex B

[28] Map of groundwater bodies in poor quantitative status per European river basin district: Figure B5 in Annex B

[29] Maps of water stress in European regions: Figure B6 and B7 in Annex B

Chemical fertiliser use has expanded significantly in most developing countries, except Sub-Saharan Africa. The developing countries' share of global fertiliser use has risen from about 10% in the 1960s to more than 60% today. Asian farmers are the major users, with an annual average of 143 kg per hectare in 2000-02 (in comparison: 6 kg per hectare in 1961-63), more than in developed countries. Higher fertiliser use accounted for at least 20% of the growth in the developing-country agriculture (excluding dryland agriculture) over the past three decades (World Bank 2007, p. 51).High-input farming has produced serious environmental problems. Fertiliser nutrient runoff from agriculture has become a major problem in the intensive systems of Asia, causing algal bloom and destroying wetlands and wildlife habitats (World Bank 2007, p. 188).

Possibilities to recycle phosphorus (P) are limited, and loss to water and adsorption in soil mean that the supply of phosphorus in agricultural systems needs to be continuously replenished. Mined rock phosphate represents the only substantial supply. Three countries control more than 85% of the known global phosphorus reserves, with Morocco having the largest share. The primary rock phosphate reserves are a finite resource. But estimations on future availability vary significantly:

> The reserves are likely to be exhausted before the end of the 21st century if trends continue (Royal Society 2009, p. 16).
> The usable reserves will be reduced by 25% in 2100, based on current demand (Malingreau et al. 2012, p. 25).

Potassium (K) supply extracted from potash is practically not limited. However, reserves are concentrated in certain geographic areas (2/3 of world production in Canada, Russia and Belarus) and a small group of companies (80% of production in eight companies) (Malingreau et al. 2012, p. 17).

Nitrogen (N) is ubiquitous in the atmosphere. Its transformation into ammonia via the Haber-Bosch process is highly energy demanding and currently uses hydrogen from natural gas. Therewith, industrial N fertilizer production is dependent from energy prices and the increasing volatile energy market, and changing natural gas availability. It is regarded as highly desirable to find alternative sources of hydrogen, such as electrolysis powered by electricity generated from renewable resources (Malingreau et al. 2012, p. 5; Royal Society 2009, p. 15).

Developments related to reserves (P and K), access (P), changing geopolitical conditions (P and K), economic development and energy costs (mainly N) and environmental constraints (N and P) could lead to temporary shortfalls and high prices in some regions of the world (Malingreau et al. 2012, p. 13).

In different crops and cropping systems as well as different regions, yield and quality can be constrained by the availability in soil of nutrients that are required by crops in small concentrations. Deficiencies of sulphur (S), calcium (Ca) and magnesium (Mg) which are classed as secondary nutrients cause significant yield reductions in some crops and regions (Royal Society 2009, p. 16).

In the European Union, total nitrogen fertilizer applications are high in the Netherlands, the Flanders region of Belgium, the Northwest of Germany, Denmark, the Po valley in Italy, the west coast of France, Ireland and England[30]. This is the result of high mineral N application rates in areas with high level of horticulture, permanent crops and intensive crop production. High manure N applications are associated with regions of concentrated livestock farming. In Central and East European countries, the total N input decreased significantly during the economic transition. In the EU-15 countries, mineral N fertilizer consumption decreased between 1990 and 2009 around 25% (EUROSTAT 2013a).

Mineral fertilizer consumption is the main input in EU-27 in 2005-08 with an average of 44% in total nitrogen inputs, followed by the gross manure input with 38%. The Netherlands, Belgium, Denmark, Cyprus, Malta and Ireland have the highest livestock densities and also have the highest rates of manure input per ha (100 kg N per ha). Romania, Bulgaria, Lithuania, Slovakia, Estonia and Latvia have the

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[30] Maps of mineral, manure and total N fertilizer application: Figure B8-B10 in Annex B

lowest livestock densities and also belong to the countries with the lowest rates of manure input per ha (40 kg N per ha). Some countries (the Netherlands, Belgium) with the highest use of manure per ha also have a high use of mineral fertilizers (100 kg N per ha), while some East European countries and Spain with the lowest rate of manure per ha (40 kg N per ha) also belong to the countries with relative low use (50 kg N per ha) of mineral fertilizers per ha. The different use of N fertilizers is also reflected in nitrogen balance[31], with higher gross nitrogen surplus in the EU-15 than in the new Member States and most Mediterranean countries (EUROSTAT 2013b).

The mineral P fertilizer application rates are high in the north of the Paris Basin (France) and the Po valley (Italy). Manure P applications and total P fertilizer applications are high in the Netherlands, Northwest of Germany, Denmark, the Po valley, west coast of France, Southern Ireland, England, North and East coast of Spain[32] (EUROSTAT 2013a). Figure 9 shows the regional level of inputs expenditures (for fertilizers, pesticides, other crop protections and purchased feed) per hectare for the period 2005-07. Especially many regions in Central and East European countries show low intensity levels. The input intensity correspondents with the regional distribution of land productivity, measured in agricultural output per hectare (Chapter 2.2).

3.2.4. Pests, diseases and weed competition

Competition from weeds, animal pests, pathogens and viruses has the potential to significantly reduce crop yields. Therewith, crop protection plays a key role in safeguarding crop productivity. Absolute losses and loss rates vary among crops due to differences in their reaction to competition of weeds and the susceptibility to attack to other pest groups. The overall loss potential is especially high in crops grown under high productivity conditions as well as in the tropics and sub-tropics where climatic conditions favour the damaging function of pests (Oerke, Dehne 2004).

Losses due to weeds, pests and diseases were estimated at 26-30% for sugar beet, barley, soybean, wheat and cotton, and 35-40% for maize, potatoes and rice (for the period 1996-1998). The assessment of loss potential of pests – losses without mechanical, biological and/or chemical crop protection measures – worldwide varied from less than 50% (barley) to more than 80% (sugar beet and cotton) (Oerke, Dehne 2004).

Animal pests can cause significant losses in food production. Locusts, larvae of Lepidoptera, and other herbivorous chewing insects can cause very substantial crop losses as can root-attacking nematodes and sucking insects such as aphids and leaf-hoppers; the latter are also important vectors of diseases caused by viruses and phytoplasma. Chemical and non-chemical approaches are available to reduce these losses.

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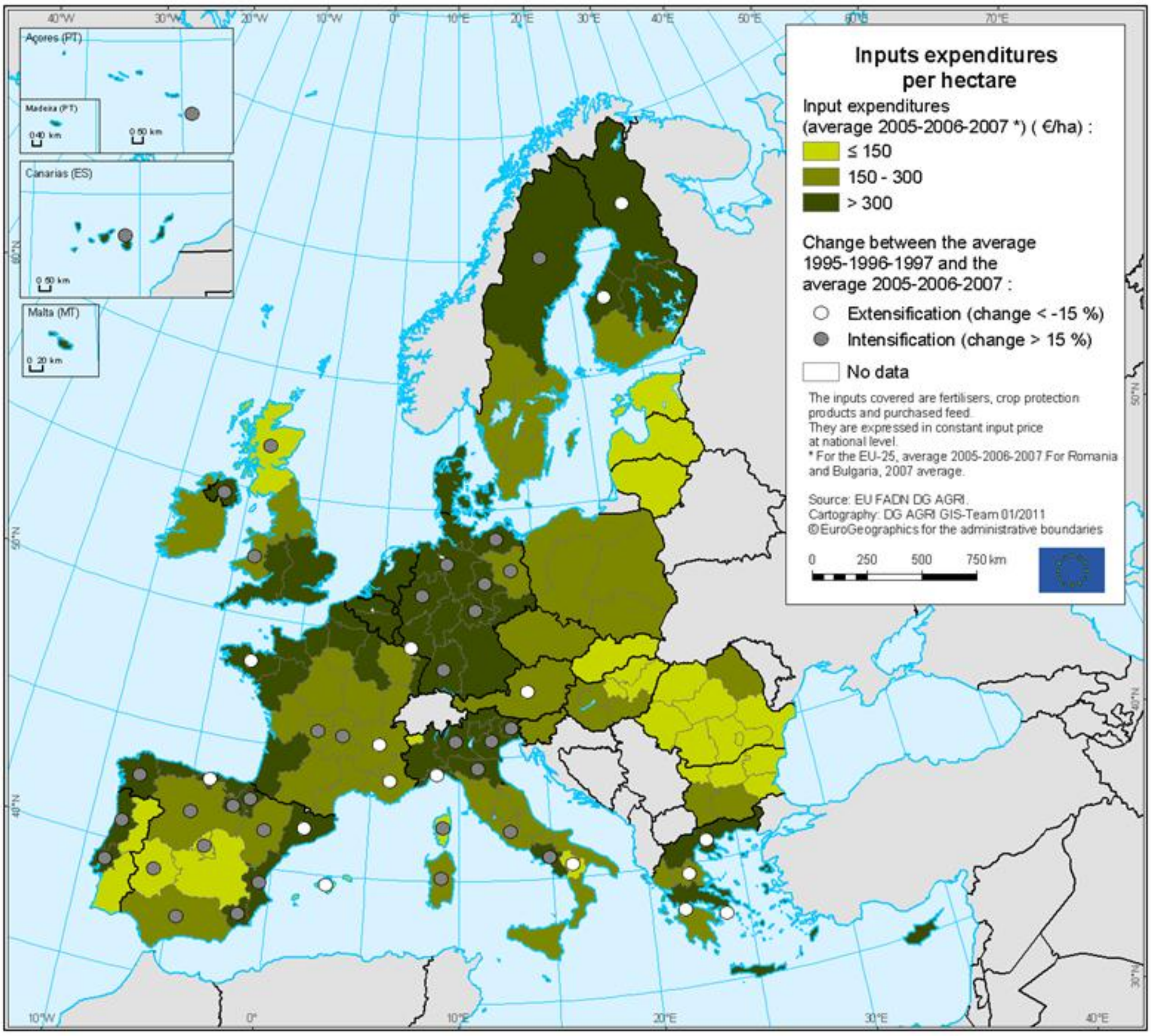
[31] Nitrogen surplus in EU Member States: Figure B11 in Annex B

[32] Maps of mineral, manure and total P fertilizer application: Figure B12-B14 in Annex B

Figure 9: Average yearly inputs expenditures (EUR/ha), EU-27, average 2005-07



Source: EUROSTAT (2013c)

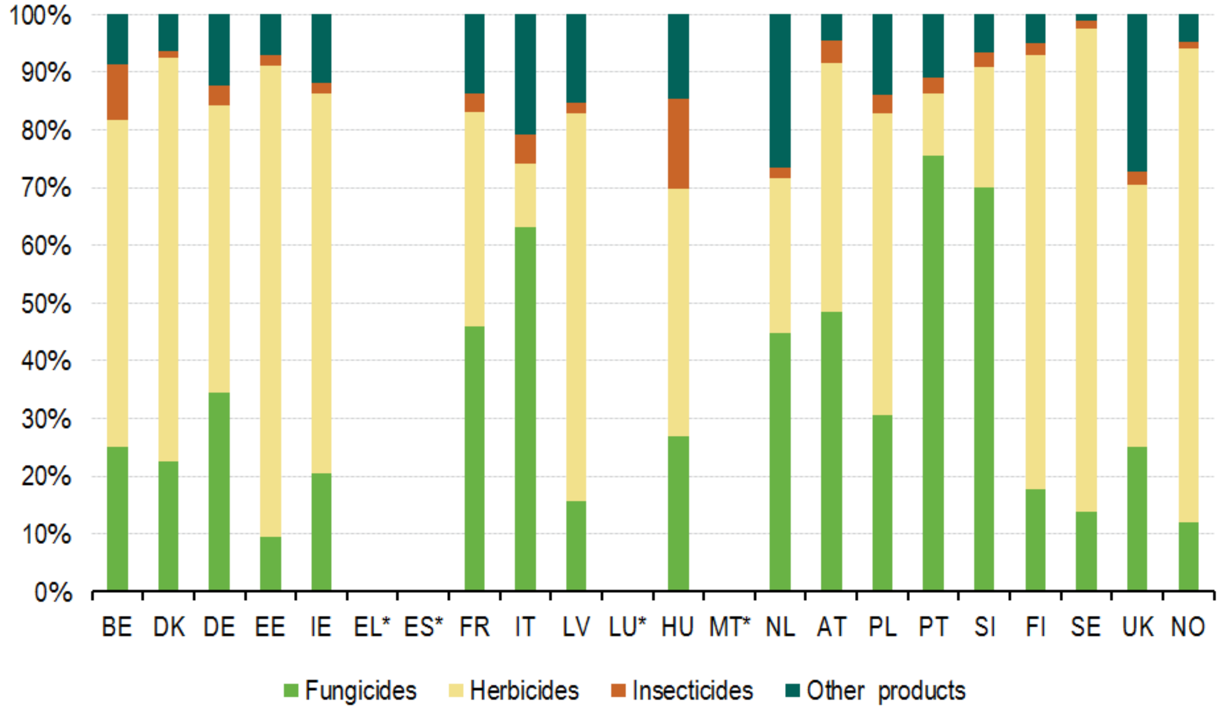
Estimated 10-15% of the global harvest is lost to plant diseases caused by fungal and bacterial pathogens (Oerke 2006; Strange, Scott2005). Plant diseases are a major impediment to the production and quality of important food stuffs. In addition to reducing yield, they are of particular concern because of their direct impacts on human and animal health due to mycotoxins and pesticide residues (Chakraborty, Newton 2011).

Among biotic constraints on crop production, weeds have the highest loss potential of 32% (Oerke / Dehne 2004). Losses due to weed competition represent a significant waste of resources (water and nutrients) that would otherwise be available to the crop. Weeds essentially represent unwanted production of a biomass that can also impede efficient harvesting. There is an increasing problem of resistance to herbicides and the establishment of populations of some weed species which are no longer readily controlled (Royal Society 2009, p. 17).

One of the major challenges to cereal production in Sub-Saharan Africa is the widespread occurrence of parasitic weeds. Probably the most important is *Striga*, which infests an estimated 20–40 million ha of farmland cultivated by poor farmers throughout this region. The tiny seeds are carried in run-off eroded soil and contaminate traded seed to infest an ever-increasing area. Every year *Striga* damage to crops accounts for an estimated US$7 billion in yield loss (about 4 million tons) in Sub-Saharan Africa (Royal Society 2009, p. 17).

In the EU, fungicides and herbicides are the most sold pesticides (in 2005), measured in quantity of active ingredient (data on sales cover agricultural and non-agricultural uses). In Germany, France, the Netherlands and Austria fungicides made up more than one third of the sales of pesticides, in Portugal, Slovenia and Italy this share was even greater than 60%. In Belgium, Ireland, Latvia, Poland and Finland herbicides made up more than half of the sales of pesticides, in Estonia and Sweden this share was even more than 80% (Figure 10).

Figure 10: Share of different types of pesticides in total sales of pesticides, 2005



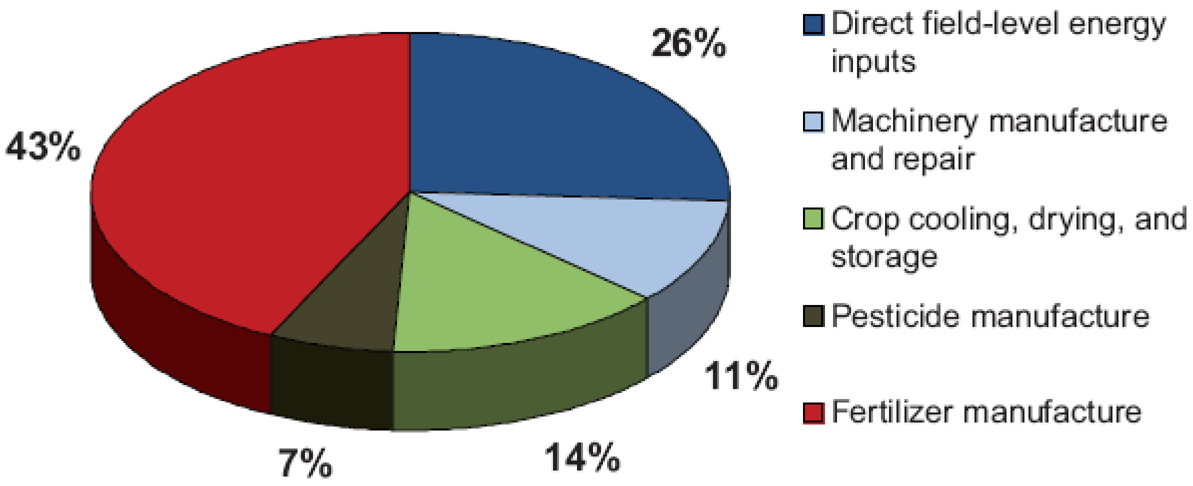
* Data were not available for LU, MT, EL and ES

Source: EUROSTAT (2013d)

3.2.5. Demand for energy input

Modern agriculture is heavily dependent on fossil energy resources. Both direct energy use for crop management and indirect energy use for fertilizers, pesticides and machinery production are of relevance (Woods et al. 2010). For intensive crop production, indirect energy consumption typically exceeds direct, on-farm energy consumption (Figure 11). Of particular relevance are nitrogen fertilizers: Although the energy efficiency of nitrogen fertilizer production has improved over time, this remains the most energy-demanding aspect of modern intensive agriculture (Pelletier et al. 2011).

Figure 11: **Production-weighted average distribution of energy inputs to the cultivation of bread and feed wheat, potatoes, barley, and oilseed rape in the United Kingdom for 2005**



Source: Pelletier et al. (2011)

The food sector in total currently accounts for around 30% of the world's total energy consumption. Primary farm and fishery production accounts for around one fifth of the total food energy demand, but produces two third of the food sector's greenhouse gas emissions (FAO 2011b, p. III).

The energy ratio – metabolisable energy in the food divided by the total amount of primary energy input in the farming process – has declined with mechanisation and intensification of the agricultural production, first in developed countries, but with the Green Revolution also in the small-scale farming of developing countries, e.g. in the India grain production from 89 in the mid 1950 years to 5.7 at the end of 1970 years (Sinha 1986). If energy prices continue to rise, high external input agriculture and the global food sector will face increased risks and lower profits, and the options of the past for increasing food productivity may become severely limited. Additionally, commodity and food prices now tend to be linked with global energy prices (FAO 2011b).

Production in many developing countries is constrained by energy inputs. Animals or human labour are often used for soil cultivation (Royal Society 2009, p. 17). In most of the developing countries, the land-holdings are small, so that it would be difficult to adopt the western model of agriculture which is almost completely mechanical and commercial energy intensive. Analysis in India and Philippines show that modern inputs such as high yielding seeds, fertilizer, pesticides, irrigation, etc. can be combined with animal power and human labour (Sinha 1986). In light of the volatility of energy prices and uncertainties with respect to long-term fossil energy availabilities, the energy intensity of food systems has important implications for food security (Pelletier et al. 2011).

4. SUSTAINABLE INTENSIFICATION AND IMPROVING CROP MANAGEMENT: REDUCING THE YIELD GAP

Three objectives of improved crop production under changing environmental conditions (e.g. climate change) are important:

- Higher production by better exploring the (genetic) yield potential
- Better input use by higher production efficiency
- Increasing the site specific yield potential by improved land productivity

Sustainable intensification means producing more food from the same area of land while reducing the environmental impacts (Godfray et al. 2010), under social and economic beneficial conditions.

In this chapter, farming management concepts, practices and technologies for sustainable intensification are discussed in two steps: First overall crop production systems are analysed (Chapter 4.1). In a second step, specific technologies and practices are evaluated (Chapter 4.2).

4.1. Production systems

Relevant crop production system approaches for sustainable intensification worldwide and in the EU are:

- Precision agriculture
- Conservation agriculture
- System of rice intensification
- Organic farming
- Agroforestry
- Integrated crop livestock production systems

These production systems are not mutually exclusive; numerous combinations (e.g., precision agriculture and conservation agriculture, conservation agriculture and agroforestry) are discussed and/or practised. The following chapters give an overview on background, objectives, key principles and state of introduction in farming practice for each production system.

4.1.1. Precision agriculture

Precision agriculture (PA) in a broad sense is information-based management of agricultural production systems or digital agriculture. The broad view of PA comprises in arable farming management a set of techniques that use information from mainly new sources that could be combined with existing data and that use agronomic rules to manage the crops. The new “precise” quality of PA derives from the consistent use of information to derive decisions and to conduct actions in a more controlled way than possible even with the “best management practices”.

Precision agriculture in a more narrow sense is the spatially variable management of crop production which is in the centre of this chapter[33] (Table 7). This approach emerged in the mid-1980s as a way to apply the right treatment in the right place at the right time (Gebbers, Adamchuk 2010). The upcoming possibilities of satellite based positioning systems were an important catalyst. Precision agriculture is rarely explicitly defined, but mostly described by explaining how it works or which technical tools are used. Key objectives are to increase the input use efficiency, to elevate productivity and to reduce environmental impacts of crop production.

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[33] Precision agriculture developments in grassland management, livestock farming and horticulture / speciality crop production are not discussed in this study due to the focus on crop production.

Table 7: Precision agriculture – overview

Criteria	Components / outcomes
Key principles	> Awareness of variation in soil and crop > Side-specific application of production inputs > Application of advanced sensor systems, remote sensing, navigation systems, variable rate technologies and decision support systems
Main objectives	> Spatially and quantitatively more accurately applied crop management measures according to local conditions > Increasing the efficiency of resource usage > Producing higher yields per land area unit > Reducing the environmental impacts of agricultural input management > Improving crop and farm management
Modifications in crop production	> Offline procedures – mapping approach > Online procedures – sensor approach > GNSS-based agricultural machinery guidance > Integrated process control and management
Strengths	> Reduction of input use > Better information-based crop management > Potential for higher economic efficiency of crop production > New possibilities for product tracking and traceability
Weaknesses	> Applications commercially available can face compatibility problems > Proper decision-support systems are lagging behind > Handling of diverse data / information > Until today linked to high-tech agriculture
Area of implementation	> Data not available
Relevant crops	> All main crops

Source: Own compilation

PA is an innovative information controlled management concept of crop production, based upon on various new or advanced technologies. These include in particular satellite-supported positioning systems, sensor technologies for data collection and geo-information systems. Using PA the existing, locally varying soil conditions and properties of crops can be recorded within an arable area. Based upon this information, analysed with special assessment systems, and with suitable agricultural equipment, plant cultivation measures can spatially and quantitatively be more accurately applied than previously. Depending upon the temporal relationship between the collection of data, decision-making and management measures, PA procedures differentiate between offline procedures (mapping approach), online procedures (sensor approach) and the combination of offline and online procedures (sensor approach with mapping overlay) (Rösch et al. 2005).

Sensor systems (or *online-systems*) relate agronomic activities on the field to information derived by different sensors which collect data in the fields (canopies, soils). They are used when dealing with rapidly-varying production factors (e.g. the nitrogen requirements of crop plants) and a real-time execution of work is required. The relevant characteristics (e.g. the nitrogen supply of crops) are recorded indirectly on the field on the basis of the optical, mechanical or biochemical properties of the crop. Such sensor based systems are used for herbicide application, N-fertilization, growth regulators and fungicides. Most of these systems are mainly single-purpose units, except the optical sensors. They can be used with any cropping measure that relies on the conditions (e.g. biomass amount, leaf area index etc.) of the canopy. The predominant cropping activity based on sensors is N-fertilization. Such sensors are also growingly used for the application of growth regulators or fungicides, deriving estimates from canopy biomass. Sensors are specifically developed to detect weeds (green colour vs. soil colour) to apply non selective herbicides. Weaknesses of the on-line procedures are the insufficient consideration to date of influences which are independent of measures taken (e.g. soil moisture levels) (Rösch et al. 2005). For the variable nitrogen fertilization, the dominating model in Europe is the YARA-N (Yara GmbH) sensor. In the rest of the world comparable sensors are being used (e.g., Green Seeker, Crop Circle, Crop Spec, OptXR).

Map based systems (or *offline systems*) have no direct temporal relationship between collection of data, issuing the machine order and execution of the management measure. In the 90ies of last century, the primary focus in developing PA techniques was to identify, map and analyse spatially varying characteristics and situations of site (soil, relief, micro-climate, etc.) and crop canopy. This led to a manifold of different solutions mainly based on the maps that could be produced from geo-coded data collected with this concept. Embracing soil quality information (e.g. from public soil quality assessments or cheap electrical conductivity scanning), data from analyses of soil samples, data from the crop canopy (plant variables measured on selected spots or using optical sensors to mapping the canopy of larger areas or whole fields) or weeds and pests/diseases, data from the performance of equipment (e.g. fuel consumption of the tractor) not ending with mapping of yields within the fields. In the US corn and soybean production, yield-mapping is the most applied PA-application with 40-45% in 2005/2006 (Schimmelpfennig, Ebel 2011).

All these data and the resulting maps (e.g. after geo-statistically correct interpolation from few points to large maps) should be used in decision making for different agronomic inputs (such as fertilizer, lime, seeds, water, pesticides) or activities (tillage intensity, sowing depth etc.) in crop production. These digital maps can be stored, analysed and managed as different 'layers' of information for one field and all fields of a farm. Intention is to transform these information layers into application maps based on agronomic principles and rules for the crop spatially variable management. Limitations arise partially due to the work involved (e.g. when determining the incidence of weeds manually) or the costs incurred (e.g. for soil sampling and analysis). The decisive weaknesses of the off-line procedure lie with the extent of administration and analysis required for large amounts of data (Rösch et al. 2005). Not many solutions are available for practical farming which consequently follow this paradigm. Growingly, consultants in Denmark, Germany, United Kingdom, USA and Canada are offering such map based solutions. The necessary tools with very user-friendly software systems are available and provided by specialized software companies (Delgado et al. 2013).

Hybrid systems (*sensor approach with mapping overlay*) intend to take into account that a single variable (e.g., canopy colour) can be used to describe certain crop situations, but is in most cases not sufficient to understand the complexity of the canopy development. For example, an actual nutrient deficit cannot be solved with additional nutrient supply through fertilizers, if the soil will probably dry out due to insufficient water supply. Based on this background, research, equipment providers as well as consultants in PA are increasingly looking for options to merge several data from different sensors ('sensor fusion') or linking sensor data with existing (mapped) information. But practical solutions are completely lacking yet.

Important *technology components* of precision agriculture are positioning systems, yield mapping, remote sensing, soil and crop sensing, variable rate technology for field machinery, and information transmission among different mobile and static electronic equipment (Mondal, Tewari 2007). In the last five years, many manufacturers of farming equipment implemented technological tools from precision agriculture in their products, and increasingly link them through software products, mostly 'cloud-based'. Modern farming equipment uses the international standardised protocols of ISOBUS (e.g., Lenz et al. 2007) for the internal control, Global Navigation Satellite Systems (GNSS) information to improve driver's performance, sensors to track the state and work quality of equipment and to inform farmer or manufacturer through telemetry. These developments are without the direct intention to use the techniques as typical PA applications such as variable rate applications in crop production.

Overall, fields of application for information controlled crop production using PA can be found in all the main work stages of the agricultural production process such as nutrient application, manure placement, weed control, disease management and water management (De Baerdemaeker 2012). Numerous examples exist of the successful application of PA to various cropping systems around the world (Bramley 2009). Adoption of precision agriculture techniques has mainly taken place in highly productive areas of Europe (Denmark, France, Germany, United Kingdom), the USA with a high proportion in contracted fertilization, including soil sampling, and Australia where resource protection is of high relevance (e.g., Controlled Traffic Farming (CTF) for soil water conservation).

Adaptation rates vary on the country, the crop and the technology implied. High adaptation rates can be found for yield monitors in the USA which are used on 40-45% of the corn and soybean fields. Variable rate technologies are used nationwide to 12% (corn) and 8% (soybeans), mainly in fertilization (Schimmelpfennig, Ebel 2011). CTF in Australia is estimated to be conducted by probably more than 40% of the farmers (Robertson 2008).

However, the rate of adoption by growers of many crops remains low (Bramley 2009) and precision agriculture has not been adopted as rapidly as envisioned in the past. Causes for the slow adoption in recent years are:

- *Compatibility problems* in hard- and software of PA-systems led to high frustrations and rejection of a not mature technology. These problems are diminishing due to international standardization (ISOBUS, Lenz et al. 2007) and improvements in data exchange standards (e.g. agriXchange, Charvat et al. 2010).
- The development of precision agriculture is characterised by *technology push*. In many cases, new PA technologies have been produced through developer push rather than user pull (Lamb et al. 2008). Insufficient involvement of end users in the design, development and dissemination of the PA-technology was the consequence (Kutter et al. 2009, Schwerdtner et al. 2010). This deficit is gradually overcome by implementing approaches of stakeholder innovation systems through researchers and manufacturers (e.g., König et al. 2012), extension service or companies promoting PA and interacting with their customers (e.g., Yohn et al. 2009) as well as by collaborative regional organizations run by farmers (e.g., Seelan et al. 2003; Schwerdtner et al. 2010).
- A further weakness is for off-line procedures the *extent of administration and analysis* required for large amounts of data, with the interpretation of the data and making of decisions using rules or suitable models, as well as with the drawing up of application maps which are sufficiently accurate while remaining inexpensive to produce. In the same way for sensor systems, insufficient accuracy or lack of plant cultivation rules for the interpretation of the sensor data collected and for the derivation of solid decision-making algorithms for the (semi)automatic transformation of sensor data into management measures can be problem (e.g., McBratney et al. 2005; Rösch et al. 2005).
- For some PA techniques a simple *transfer to other regions* is not possible. Especially the variable rate application technologies need regional, sometimes site specific adaptation. The local responses to the varying resource have to be known or to be determined (e.g. for nitrogen-/biomass-sensors).

High-tech solutions are not feasible for small-scale farmers in developing countries. But chances are seen for "soft" PA concepts which depend mainly on visual observation of crop and soil and management decision based on experience and intuition, supported by knowledge from extension services and through training, rather than on statistical and scientific analysis (Mondal, Basu 2009).

With the broad spread of cell phones, new possibilities open for easy to handle applications of more precision crop management also in developing countries. For example, so called site-specific nutrient management (SSNM) is a simple form of precision farming that matches nitrogen application to local field conditions and balances them with inputs of phosphorus and potassium, which can increase yields, nutrient use efficiency and profits. Nutrient recommendations can be received by answering roughly a dozen questions by smart phone or regular cell phone. The system is now operating across the Philippines and should be running soon in Indonesia, Bangladesh, and parts of India and China (Fisher 2012). With such approaches, changes are seen to make a major contribution to reduce fertilizer inputs and increase yields in the intensive farming systems of developing and transition countries.

Impacts of precision agriculture

Assessment of yield impacts of single precision agriculture technologies are reported on base of field experiments, experimental and practical farms, and survey data. For the USA, higher yields are reported for adapters of yield monitors, global positioning system mapping and variable-rate technology fertilizing in corn and soybean, based on data from the Agricultural Resource Management Survey (Schimmelpfennig, Ebel 2011). Problem of survey data is that it cannot be distinguished between technology impacts, and learning effects and overall better management capacities of adopting farmers. Practical experience from Australian grain farms show that the use of variable rate technology saved fertilizer or increased yields, depending on the local farming situation (Mayfield et al. 2008, p. 43).

Site-specific lime management is seen as one of the most feasible strategies for variable rate applications (see chapter 4.2.2). On-the-go soil sensors are available, but difficult to implement. They can provide accurate pH information at a rather low cost. So far, few results concerning yield increases or lime saving due to variable rate liming have been published (Jensen et al. 2012).

Main impact of site-specific weed control is the reduction of herbicide use. For example, experiments at a German research station with maize, wheat, barley and sugar beet over 4 years had the result that on average 54% of the herbicides could be saved. Savings were strongly dependent on crop, weed type and year (Timmermann et al. 2003). Today, site-specific weed management seems only appropriate in case of a great variability in soil quality, nutrient composition and weed coverage, and if expensive equipment is exploited intensively (Takàcs-György 2008).

Controlled Traffic Farming (CTF)[34] allows natural processes to repair damaged soil and prevent further soil degradation A full restoration to natural conditions may be possible after years of practicing CTF. Farmers in Australia have experienced 10-23% increases in yield resulting from the combination of zero tillage (Chapter 4.1.2.) with CTF (Tullberg et al. 2007). Additional impacts are reduced fuel consumption, lower labour costs and seed savings (Jensen et al. 2012).

Spatially variable rate applications of inputs were found to be economically for nitrogen fertilizer (e.g., Meyer-Aurich et al. 2010; Murray, Yule 2007), herbicides (e.g., Timmermann et al. 2003), irrigation (Hedley et al. 2009) and controlled traffic farming (e.g., Tullberg et al. 2007). A review of 210 profitability studies had the result that 68% reported benefits from some sort of PA technology (Griffin, Lowenberg-DeBoer 2005). Profitability of PA approaches is influenced by the costs for investment, learning and management on the one hand and by the gains from achievable input savings and higher yields on the other hand, moderated by the development of market prices (Rösch et al. 2005, p. 89 ff.). Payback period

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[34] In controlled traffic all equipment wheels are restricted to compacted permanent traffic lanes, so that soil in the crop beds and traffic lanes can be managed respectively for optimum cropping.

and minimum application area are dependent from the constellation of costs and gains. Precision agriculture technologies are not scale-neutral.

Precision agriculture in the EU

Rates of precision agriculture adoption in Europe are not accessed recently, but older surveys (Reichardt, Jürgens 2009; Fountas et al. 2005) found adaptation rates in some European countries between 3% and 8%. In Germany, most of the users are predominantly located in eastern Germany where farm and field size is considerably larger than the average (Reichardt, Jürgens 2009). Exact figures on the current use of different precision farming technologies do not exist.

Reliable data on the use of precision agriculture would need representative surveys which include all types of farms. Due to the open understanding of PA, surveys should specifically cover the different approaches and technologies of precision agriculture so that their relevance and development can be assessed. Some studies have been done on awareness, additutes and constraints. But more assessment is desirable about performance and profitability of PA approaches. Better information about benefits can contribute to the spread of precision agriculture.

Constraints for the introduction of precision agriculture

The most important *barriers for the introduction of precision agriculture in Europe* are:

- *Awareness and knowledge*: Information about technological possibilities and profitable applications are not always sufficiently available, especially in the form of on-farm evidence. The perception is dependent from the educational background of farmers.
- *Variability of cultivation conditions*: A certain variation of soil conditions and crop development is a precondition for profitable applications of precision agriculture. These are not always given.
- *Farm structure*: Precision agriculture is not scale-neutral, i.e. PA techniques demand a minimum application area to be economically valid. Until today, PA is linked to high-tech, intensive crop production, and lesssuitable for smaller-scale farming.
- *Capability and training:* Precision agriculture approaches are integrative and interdisciplinary. The different interactions of growth factors in the yield development become even more important in agronomic understanding with PA. Vocational and technical schools are lacking behind to address PA issues.
- *Technically mature products*: Some PA approaches are still in the state of research and development. For example, hyper-spectral sensor applications for pre-harvest quality assessments or deficits in micro-nutrients are under development, but not commercially available yet.
- *Proper decision-support systems*: More data and knowledge about their spatial distribution is insufficient without agronomic understanding how to interpret these data and how to convert such information into cultivation measures. The development of decision-support systems are lagging behindare not yet well integrated.
- *Demand for management time and skills*: Management time is a scarce resource in modern agriculture. Handling of divers data and information and their conversion in management decisions is still time consuming and difficult. PA technology can reach beyond innovators to the majority of farmers, if it becomes easier to use and less time consumingmore accessible.

Key hindrances cited to the adoption of precision farming practices in speciality crop production are (Upadhyaya et al. 2010):

- Lack of commercial yield monitors for many horticulture crops;
- Lack of reliable and inexpensive sensors;

- Cost and complexity of the technology;
- Virtual non-existence of scientifically and economically sound decision support systems.

4.1.2. Conservation agriculture

Conservation agriculture (CA) (Table 8; extensive description and discussion in Friedrich et al. 2009) is characterised by *three principles* (see FAO 2008, p. 120; Hobbs et al. 2008):

- Continuous *minimal or no mechanical soil disturbance* (e.g., non-tillage in combination with direct seeding or direct planting);
- *Permanent organic-matter soil cover* (e.g., crop residues, cover crops);
- *Diversified crop rotations* (or plant associations in the case of perennial crops).

Conservation agriculture aims to prevent soil degradation and to preserve and/or enhance soil fertility by strengthening natural biological processes above and below the ground. The *objectives* to be achieved with CA are in detail (STOA 2009, p. 81):

- to provide and maintain an optimum environment in the root-zone of crops;
- to ensure that water enters the soil so that plants suffer less or no water stress and surface runoff is reduced;
- to favour beneficial biological activity in the soil to maintain and rebuild soil architecture, to compete soil pathogens, to enhance soil organic matter, and to contribute to capture, retention and slow release of plant nutrients;
- to avoid physical and chemical damage to roots that disrupts their effective functioning or limits their nutrient uptake.

Table 8: Conservation agriculture – overview

Criteria	Components / outcomes
Key principles	> Minimal or no mechanical soil disturbance > Direct seeding or planting > Permanent organic-matter soil cover > Diversified crop rotation
Main objectives	> Preservation / Enhancement of soil fertility > Prevention of soil degradation > Better water infiltration and preservation in soils > Stabilisation / enhancement of yield
Modifications in crop production	> New equipment for direct seeding / planting > Modification of weed management practice > Management of crop residues, cover crops and mulching > Change of long established thinking (ploughing)
Strengths	> Higher stable yields > Enhancement of land productivity potential > Reduction of soil degradation problems > Possibility of second planting (dependent from local conditions) > Reduction of fuel-energy input > Reduced greenhouse gas emissions
Weaknesses	> Need for local adaptation > Investment in seeding / planting technique > Possible competition for crop residues (particularly in arid / semi-arid regions) > Weed control with synthetic pesticides
Area of implementation	> Worldwide: approx. 125 million ha (2011), 9% of arable land > EU-27: 1.35 – 3.5 million ha (2010), 1.3 – 3.4% of arable land
Relevant crops	> Cereals (maize, wheat) > Oil crops (soybeans, rapeseed, sunflower) > Roots and tubers (cassava, potato) > Perennial crops

Source: Based on Friedrich et al. (2012); Kassam et al. (2009); Meyer (2010); STOA (2009)

CA addresses key problems in tropical and subtropical areas: the danger of erosion due to rainfall is high, soils are usually poor and eroded, and temperatures are high, with the result that decomposition is rapid (Meyer 2010). In dry climates, CA improves soil porosity from which results two effects: a greater proportion of the incident rainfall enters into soil, and the better distribution of pore-spaces of optimum size brings a greater proportion of the received water at plant-available tension. Improved soil organic matter and therewith soil fertility under CA cause better nutrient supply and water retention (Kassam et al. 2012). The benefits of CA are also relevant in temperate regions.

The Conservation agriculture development to date has been associated with rainfed arable crops. But CA can be used in rainfed and irrigated farming systems and is suitable for different crop types such as grain crops (including rice), roots and tubers, vegetables, perennials and agroforestry systems (STOA 2009, p. 16). CA is predominantly used in the cultivation of stable crops and feeds.

No-till agriculture in the modern sense originated in the USA in the 1950s. In the past two decades, no-till has increased most strongly in Latin America, where it is now practised on around 30% of the cropland (Kassam et al. 2009). Today, South America is the leading region in CA implementation (Table 9). Global data of CA adoption are not officially reported, but collected from local farmers' and interest groups. Based on these data, the worldwide spread of CA in 2011 was about 125 Million ha (Friedrich et al. 2012).

Table 9: Area under CA by regions

Continent	CA Area (ha)	Percentage of total CA area (%)
South America	55,464,100	45
North America	39,981,000	32
Australia & New Zealand	17,162,000	14
Asia	4,723,000	4
Russia & Ukraine	5,100,000	3
Europe	1,351,900	1
Africa	1,012,840	1
World total	124,794,840	100

Source: Friedrich et al. (2012)

At the farm level, conservation agriculture cannot be reduced to a simple standard technology. Thus, the interactions between the possible recommended technological components and the location-specific conditions of farming must be adequately taken into account. Consequently, the standardised "best bet" production technologies approach tend to be of limited relevance and value for many farmers because CA practices tend to be knowledge-intensive and farmers themselves must become involved in fine-tuning the transformation and application of the principles into site-specific and farm-specific practices (STOA 2009, p. 82).

Machinery, tools and equipment have been developed to cater for three levels of power usage: manual power, animal traction and motorised equipment. The success of CA depends on the effective management of operations dealing with: (a) land preparation, (b) cover crops and weeds, (c) direct seeding and (d) harvest and residues (STOA 2009, p. 82). Although large-scale farmers are important actors, CA is also used by small-scale farmers.

Impacts of conservation agriculture

Conservation agriculture can *increase yields and profit margins* (example in Figure 12). In dry Mediterranean climates, yield differences resulting from improved soil moisture and nutrient availability have been reported in the range of 20 to 120% and more between CA systems and tillage systems. CA is a practice for reversing SOM decline and the associated loss of soil fertility. Equally, CA is capable of reducing the risk of soil erosion and landslides (Kassam et al. 2012). Therewith, CA has the potential to improve site specific yield potentials.

Figure 12: Relative yield and profit of different crops under conservation agriculture compared to conventional soil management

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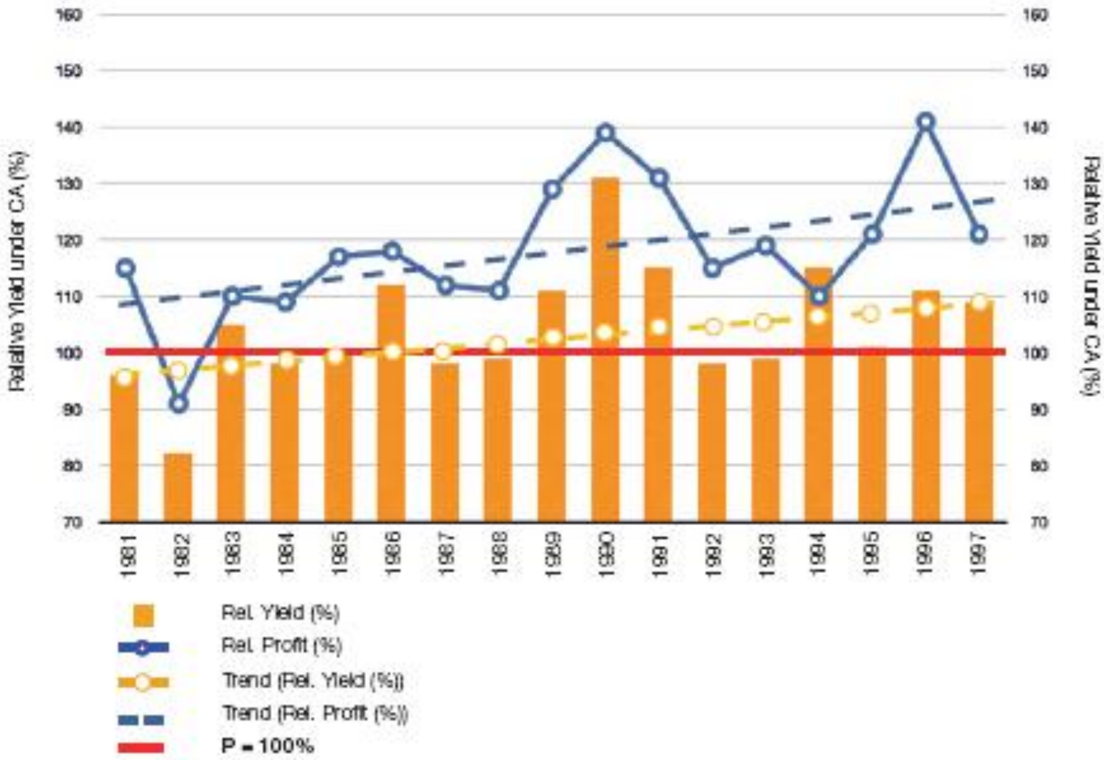


Source: Basch et al. (2012), p. 31

CA implies changed weed management (Stagnari et al. 2009). Weed control by tillage has to be replaced by use of herbicides and/or soil cover management. There is no evidence of an increase in the use of herbicides under CA systems when compared to conventional tillage farming. Instead, there is a shift in application timing and towards the use of contact herbicides which are less persistent in the environment than the more frequently used residual herbicides in conventional farming. In countries such as Canada and Australia, which have agro-ecological conditions similar to Europe, herbicide use per tonne of output is lower in CA systems with integrated weed management than with conventional tillage (Basch et al. 2012, p. 8).

Conservation agriculture in the EU

In Europe, conservation agriculture is not widespread. Different assessments exist on the spread of CA in Europe. A review reports 1,536,100 ha as area under CA. No-till systems are assessed to not exceed 2% of the agricultural cropland (Kassam et al. 2009). The European Conservation Agriculture Federation (ECAF) estimates that there are some 1.3 million hectares of arable cropland under CA system in Europe, mainly in Spain, France, Finland, United Kingdom, Italy, Portugal and Switzerland. Perennial crops further contribute up to 1 million hectares consisting of olive and other fruit trees (Basch et al. 2012, p. 12; ECAF 2013). The Soco project reports higher rates of uptake of no-tillage with 2.5 to 4.5% of total arable land in the Czech Republic, Slovakia, Spain and the United Kingdom, and 4.5 to 10% in Finland and

Greece. Uptake of reduced tillage is assessed to be practiced on 40 to 55% of arable land in Finland and the United Kingdom, and on 20 to 25% in France, Germany and Portugal (Louwagie et al. 2009, p. VIII). The results from the EUROSTAT Farm Structure Survey 2010 (Table 10) differ and show rates of zero tillage (no tillage) over 5% of the arable land for Denmark, Estonia, Spain, Romania and Finland. High percentages (over 30%) of arable land managed with conservation tillage (zone, strip or row tillage, surface incorporation of crop residues and cover crops) can be found for Bulgaria, Czech Republic, Germany and Cyprus. The zero tillage area for EU-27 sums up to around 3.5 million ha or 3.4% of the arable land. Therewith, the soil erosion and soil fertility problems in the EU (Chapter 3.2.1) are not addressed adequately and the productivity improvement potentials not explored sufficiently.

Implementation of conservation agriculture in Europe is driven by two factors (Basch et al. 2012, p. 15, 32):

> The adoption process is on one side farmer-driven, primarily motivated by reductions in the operating cost of machinery, fuel and labour.

> On the other side temporary support mechanisms in the frame of agri-environmental measures play a role in some Member States (or regions of Member States) such as Germany, Italy and Spain.

Constraints for the introduction of conservation agriculture

The most important *barriers for the introduction of CA in Europe* are:

> *Mindset*: CA constitutes a major departure, and a paradigm shift from the way agriculture is practiced conventionally, demanding a change of mindset.

> *Awareness for soil degradation problems*: Farmers need to recognise the necessity to reduce soil degradation problems and the potentials of CA to address this issue.

> *Adaptive research and demonstration efforts*: Principles of CA need to be adopted to specific farming situations. Therewith, the undertaking of adaptive research and chances of learning from farmer to farmer are important.

> *Change of weed management*: Weeds are often an initial problem that requires integrated weed management over time to get them under control.

> *Availability of biomass*: Especially in arid and semi-arid regions, concurrence with other biomass uses can be a problem.

> *Availability of machinery*: Specialised direct seeding and/or planting equipment is more easily available for large-scale farmers. Smallholders need a different set of machinery or a specific system of custom hire services.

> *Profitable alternative crops for diversified crop rotations*: Higher profitability of a restricted number of crops and economic gains from specialisation are obstacles for the diversification of rotations.

> *Availability of incentive programmes*: The change to CA demands some investments and the full benefits of CA take time to materialise. Soil physical and biological health also takes time to develop. Support for the transition period helps to spread CA.

Table 10: Conservation tillage and zero tillage in EU-27, 2010

EU Member State	Zero tillage		Conservation tillage	
	Area (ha)	Percentage of arable land(%)	Area (ha)	Percentage of arable land (%)
Bulgaria	16,500	0.53	1,727,550	55.28
Czech Republic	40,820	1.62	812,390	32.27
Denmark	137,130	5.67	132,870	5.49
Germany	146,610	1.24	4,470,300	37.73
Estonia	42,140	6.58	85,370	13.34
Ireland	10,000	0.99	26,110	2.58
Greece	34,360	1.94	327,190	18.51
Spain	701,270	6.21	2,223,580	19.70
France	530,270	2.88	4,619,950	25.13
Italy	283,920	4.05	300,970	4.29
Cyprus	270	0.32	56,020	66.01
Latvia	11,340	1.01	71,970	6.43
Lithuania	19,280	0.91	147,270	6.96
Luxembourg	440	0.71	15.470	24.95
Hungary	44,170	1.16	409,670	10.79
Malta	0	0,00	0	0,00
Netherlands	590	0.06	103,220	10.10
Austria	28.330	2.07	326,720	23.83
Poland	403.180	3.73	466.670	4.32
Portugal	29,970	2.55	160,090	13.65
Romania	583,820	7.03	192,530	2.32
Slovenia	2,480	1.47	14,690	8.69
Slovakia	33,020	2.46	226,400	16.85
Finland	167,750	7.44	378,380	16.79
Sweden	15,820	0.61	304,490	11.66
United Kingdom	219,140	3.69	1,457,110	24.51

Source: EUROSTAT (2013d)

4.1.3 System of rice intensification

The System of Rice Intensification (SRI) (Table 11; extensive description and discussion in Uphoff and Kassam 2009) is an innovation in rice production systems and comprises a set of modified practices for managing rice cultivation. These changes to often age-old cultural practices of rice cultivation can be seen as a civil society innovation whose origins lie outside the scientific research system (Uphoff 2006). The *main operational principles of SRI* are as follows (STOA 2009, p. 86):

- *Careful transplanting of younger seedlings*: Young seedlings, 8-12 days old, instead of the usual 3-4 weeks old seedlings, are used. Transplanting should be done very carefully but quickly, taking special care to protect the young roots.
- *Wider spacing of plants*: The recommendation is one plant per hill established in a square pattern. The aim of the wider spacing in a square pattern is to give both roots and canopy more room to grow, for taking up nutrients and capturing sunlight.
- *Aerobic soil conditions*: The paddy soils should be kept moist but not continuously flooded and saturated to avoid suffocation and degeneration of rice plant roots and to support more abundant and diverse populations of aerobic soil organisms.
- *Enhanced soil organic matter*: As much as possible compost or mulch should be used to enhance the soil organic matter and to “feed” the soil biota which will help to feed and protect the growing plants.

Table 11: System of rice intensification – overview

Criteria	Components / outcomes
Key principles	> Careful transplanting of younger seedlings > Wider spacing of plants > Aerobic soil conditions > Enhanced soil organic matter
Main objectives	> Enhancement of soil fertility > Better development of plant roots > Higher yields by more profuse growth of tillers, leaves, panicles (ears of grain) and grains themselves
Modifications in crop production	> Changed nursery and transplanting > Modification of weed management > Modification of irrigation regime > Intensified weed control > Mulch or compost application
Strengths	> Higher yields > Enhancement of land productivity potential > Successful with traditional, local varieties and with new, improved varieties > Reduction of needed irrigation water
Weaknesses	> Need for local adaptation, new knowledge > Improved farmer skills for transplanting needed > Controlled irrigation necessary > Availability of biomass > Rethinking of age-old practice of rice cultivation
Area of implementation	> Worldwide: approx. xx million ha, xx% of arable land > EU-27: No application
Relevant crops	> Rice > Sugarcane > Cereals (wheat, finger millet)

Source: Based on Meyer (2010); STOA (2009)

The system of rice intensification can be fully organic since resulting plants are more resistant to pests and diseases; but if not enough biomass or labour is available to supply the soil with organic matter, mineral fertilisers can be used. Also, agrochemicals can be used for pest control but are usually not needed or uneconomic. Generally the best yields and highest incomes with SRI methods come from organic crop management. SRI methods are successful with both traditional, local varieties and with new, improved varieties and hybrids. Therewith, these methods can be used within the full range of subsistence to 'modern' agricultural production systems. The key is to enable the rice plants and the crop as a whole to express their full genetic potential under the soil-water-nutrient management conditions that enhance and maintain soil fertility and its productive capacity. So, in this regard SRI is compatible and convergent with Conservation Agriculture. The SRI practices, taken together, produce larger, longer-lived plant roots and more abundant, diverse and active soil biota to support a greater number of panicle-bearing tillers that have higher number of spikelets and seeds, and mature synchronously and early (Meyer 2011).

SRI is a relatively young innovation that is still evolving. It has now been demonstrated and become widespread in all world regions except Europe and North America. Its methods have proved to be productive in a wide variety of agroecosystems. In the meantime, the approach has also been applied to other crops such as wheat, finger millet and sugar cane. Estimation is that SRI is currently used by one million small farmers producing rice around the world on over one million hectares. The greatest adoption of SRI methods has been in Asia, where 90 per cent of the world's rice is produced. SRI practices such as timing and spacing, and increasingly in-situ biomass production, are always to be adapted to local conditions and cropping systems (STOA 2009, p. 90).

Important *conditions for a successful introduction of SRI* in developing countries with small-scale farming are (Meyer 2011):

- Openness to change traditional thinking and practice of rice production;
- Availability of organic fertilizer for enhanced soil organic matter;
- Feasibility of changed weed management;
- Incentives for saving of irrigation water;
- Availability of trained workers for the transplanting of young seedlings;
- Participative approaches for extension and advisory services (e.g., farm field schools).

4.1.4. Organic farming

Organic Farming (OF) (Table 12; extensive description and discussion in Hoffmann 2009) relies on ecological processes, biodiversity and cycles adapted to local conditions. Rather than using external inputs, organic farming focuses on input optimisation and deliberately renounces readily soluble mineral fertilizers, synthetic pesticides and performance stimulants (Meyer 2010).

International principles and standards are defined by the International Federation of Organic Agriculture Movements (IFOAM). The *four principles*, including guidelines that go beyond the process of agricultural production itself, are (IFOAM 2008):

- *Principle of health*: Organic Agriculture should sustain and enhance the health of soil, plant, animal, human and planet as one and indivisible.
- *Principle of ecology*: Organic Agriculture should be based on living ecological systems and cycles, work with them, emulate them and help sustain them.
- *Principle of fairness*: Organic Agriculture should build on relationships that ensure fairness with regard to the common environment and life opportunities.
- *Principle of care*: Organic Agriculture should be managed in a precautionary and responsible manner to protect the health and well-being of current and future generations and the environment.

Table 12: Organic Farming – overview

Criteria	Components / outcomes
Key principles	> Principle of health > Principle of ecology > Principle of fairness > Principle of care
Main objectives	> Regeneration and maintenance of soil fertility > Optimisation of input use > Closing of nutrition circles > Higher biodiversity > Healthier food
Modifications in crop production	> Diversified crop rotations > Renouncement of readily soluble mineral fertilizers, synthetic pesticides and performance stimulants > Green manure, animal manure and compost > Nitrogen supply with legumes > Maintaining and enhancing ecological valuable elements of the farming landscape
Strengths	> Legally defined production method > Separated food chains with price premium > Preservation / enhancement of land productivity potential > Agro-ecological pest and disease management > Higher yields in comparison to conventional low external input production in developing countries
Weaknesses	> Higher workload > Costs of certification and controls > Conversion costs > Need for local adaptation > Lower yields in comparison to intensive production in industrialised countries
Area of implementation	> Worldwide: approx. 37 million ha, 0.9% of total agricultural land > EU-27: 9.5 million ha, 5.4% of total agricultural land
Relevant crops	> All crops

Source: Based on Meyer (2010); STOA (2009); Willer et al. (2013)

In the context of growing international demand for healthy food and its global trading, a highly controlled certification system based on precepts and rules for production has been developed. Additional unique characteristic of organic farming is that it represents a legally defined production method for food (Codex Alimentarius Commission 2009; EC 2007). Most EU Member States have implemented area payments to support conversion to and continued organic production. Although all EU Member State support schemes for organic conversion and maintenance are underpinned by the same EU regulation (1968/2005 for 2007-2013), there is considerable variation between countries in payment rates, eligibility conditions and requirements (Stolze, Lampkin 2009). Finally, organic farming can also be part of a movement with agro-political and ideological-philosophical influence and/or of a lifestyle.

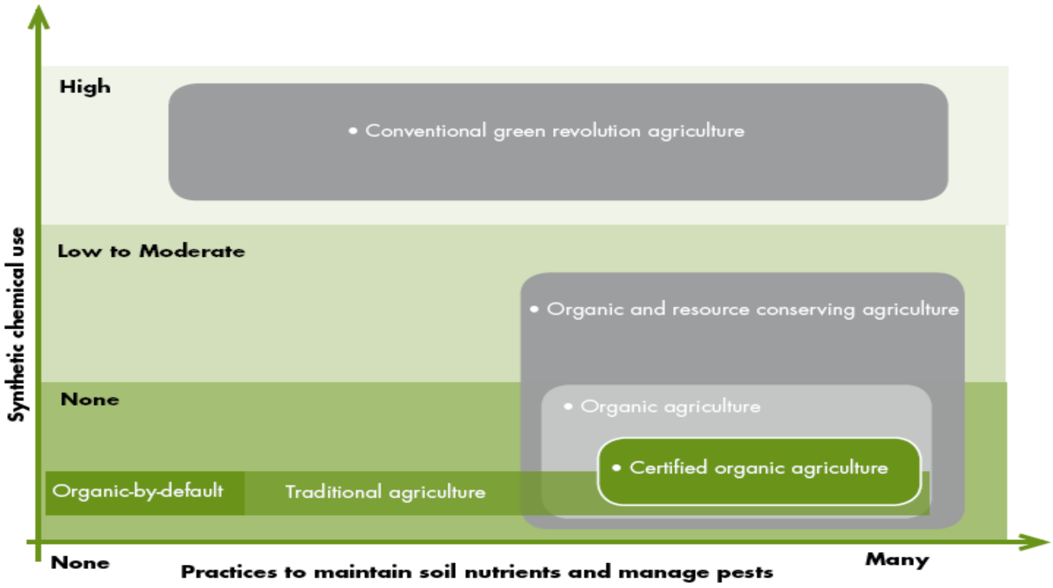
The organic farming production systems show similarities concerning their key technologies on all continents:

> Use of a high biodiversity through crop rotation, agroforestry and/or combination of plant and livestock production;
> High ranking of compost and, if available, animal dung;
> Often a higher proportion of manual labour;
> Openness towards new technical solutions.

The cultivation system allows the use of simple mechanisation solutions as well as the application of modern machines that may be combined with animal power up to the use of precision farming elements.

Organic farming in developing countries is embedded in similar agricultural production systems. Certified organic agriculture produces for national and/or international markets. Beside the certified organic – only these are covered in statistics – exists more organic farming which follows more or less organic production principles without certification (Figure 13). Additionally, a number of common points exist also with other resource conserving production approaches. In the so called "Organic-by-default", farmers also do not use synthetic fertilizers and pesticides, in this case due to poverty and limited access to external inputs. But their practices do not normally include maintenance and enhancement of ecological processes (Bennett, Franzel 2009; UNCTAD 2006, p. 144).

Figure 13: Various agricultural production systems and their interrelationships in terms of practices and inputs



Source: Bennett, Franzel (2009), p. 4

In 2011, around 37 million hectares were organic agricultural land (including in-conversion area), managed by nearly 1.8 million farmers worldwide (Table 13). Of this total area, around one third is located in developing and emerging countries (6.9 million ha in Latin America, 3.7 million ha in Asia, 1.1 million ha in Africa). The share of Organic Farming area is low in most developing countries. But many organic producers are located in developing and emerging countries. The countries with highest numbers of organic farms are India (547,600 producers), Uganda (188,600) and Mexico (169,600). More than two third of certified organic producers are in Africa and Asia (Willer et al. 2013). Nonetheless, the percentage of organic producers is low in most countries.

Table 13: Global organic farming, 2011

Region	Organic agricultural land		Organic producers	
	Area (ha)	Regions' share of global organic agricultural land (%)	Producers	Regions' share of total agricultural producers (%)
Africa	1,073,657	2.88	540,988	30.08
Asia	3,706,280	9.95	619,439	34.44
Europe	10,637,128	28.56	291,451	16.21
Latin America	6,857,611	18.41	315,889	17.56
Northern America	2,790,162	7.49	16,659	0.93
Oceania	12,185,843	32.71	14,138	0.78
Total	37,245,686	100.00	1,798,359	100.00

Source: Willer et al. (2013), p. 40, 62

Almost two-thirds of the organic agricultural land worldwide in 2011 was grassland/grazing areas (23.2 million ha). The cropland area – arable land with 6.3 million ha and permanent crops with 2.6 million ha – constitute more than a quarter of the organic agricultural land. Europe with 4.4 million ha of organic arable land contributes around 70% of the global arable land of organic agriculture (Willer et al. 2013). In Africa, Latin America and Oceania, the shares of grassland and those of permanent crops are, compared to Europe and North America, relatively high. This can be attributed to the fact that export plays an important role – either for meat products or for permanent crops. The most important organic export crops are coffee, olives, cocoa and sugarcane (STOA 2009, p. 95).

Impacts of organic farming

The yield effects of organic farming in developed and developing countries is quite different. For developing countries, the comparison of organic or semi-organic production to locally prevalent methods under field conditions shows higher yields in organic farming, from 157% for grain products over 270% for starchy roots to 400% for legumes (pulses) (Badgley et al. 2007). In the case of a meta-analysis of current scientific literature on yield comparisons, which mainly included data for developing countries from high-input systems with irrigation or coming from experimental stations for the conventional production, the organic yields are 43% lower in organic agriculture (Seufert et al. 2012). Another meta-analysis reports that in developing countries organic yields are 84% of those obtained under conventional agriculture (de Ponti et al. 2012).

For developed countries, Badgley et al. (2007) estimated a yield ratio (ratio of organic : non-organic yield) 0.93 for grain products, 0.89 for starchy roots and 0.82 for legumes. Result of the analysis of Seufert et al. (2012) for developed countries was 20% lower yields for organic production in average. A very similar result achieved de Ponti et al. (2012) with an overall relative organic yield of 79%. The relative organic yields were lowest in Northern Europe (Finland, Sweden, and Norway) with 70% and in North-western Europe (Denmark, Germany, Netherlands, and United Kingdom) with 73%. In Central Europe (Austria, Switzerland) the relative yields were 88%, and in Southern and Eastern Europe similar to the overall average for developed countries (de Ponti et al. 2012).

Yield differences between organic and conventional agriculture are highly contextual. When using best organic management practices are closer to conventional yields. Organic Farming also performs better under certain agro-ecological conditions such as organic legumes or perennials, on weak-alkaline soils or in rain-fed conditions. Organic yields are often low in the first years after conversion and gradually increase over time due to improvements in soil fertility and management skills. The meta-analysis shows that organic performance improves in stud8ies that lasted for more than two seasons or were conducted on plots that had been organic for at least 3 years (Seufert et al. 2012). The 30 years farming system trial at the Rodale Institute (USA) has the result that overall organic yields match conventional yields. In years of drought, organic corn yields were around 30% higher than conventional (Pimental et al. 2005; Rodale Institute 2011).

These results are based on results from field experiments, experimental and commercial farms. They cannot be readily up-scaled to higher system levels (de Ponti et al. 2012). For example, intensive organic food consumers change their diets. Their reduced consumption of meat products decrease disproportionately the required land for food production so that additional land demand of organic crop production can potentially be more than compensated (TAB 2012, p. 143).

Positive environmental impacts of organic farming – in difference to conventional farming, which also contribute to improved site specific yield potentials, are:

> Under organic management soil loss is greatly reduced. Soil organic carbon (SOC) concentrations, stocks and sequestration rates are higher in organically farmed soils. Soil biochemical and ecological characteristics appear also improved. Furthermore, organically managed soils have a much higher water holding capacity (Gattinger et al. 2012; Gomiero et al. 2011).

> Organic farming systems generally harbour a larger floral and faunal biodiversity than conventional systems. The advantages of organic farming can be found on the farm land and attached areas such as hedges. Organic Farming can contribute to an enhanced landscape biodiversity (Rahmann 2011; Gomiero et al. 2011).

> Concerning nitrate and phosphorous leaching and greenhouse gas emissions, organic farming scores better per production area. However, given the lower land use efficiency or organic farming in developed countries, this positive effect expressed per unit product is less pronounced or not present at all (Mondelaers et al. 2009).

> Organic agriculture has higher energy efficiency (input output ratio), but reduced productivity due to lower yields in developed countries (Gomiero et al. 2011).

None of the differences in environmental effects can be attributed to a standalone management practice; it is the combined effect of several modifications to the conventional practices that results into the lower environmental pressure per area of production (Mondelaers et al. 2009).

The overwhelming majority of comparative case studies show that organic farms are more economically profitable, despite the frequent yield decrease in developed countries. The higher outcomes generated by organic agriculture are due to premium prices and predominantly lower production costs (Nemes 2009).

Organic farming in the EU

Organic farming in Europe has rapidly and continuously developed since the beginning of the 1990s. In the European Union (EU27), more than 9.5 million hectare were managed organically by around 235,000 producers in 2011 (Table 14). This constitutes 5.4% of the agricultural area[35]. The differences between member states are substantial. Five Member States (Austria, Czech Republic, Estonia, Latvia and Sweden) have more than ten percent of the agricultural land under organic farming (Willer et al. 2013, p. 219). In Italy as an exception, the number of organic holdings had decreased in the first half of the 2000er years as a consequence of decreased agri-environment payments together with lower prices of organic products (EC 2010a, p. 15).

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[35] The Farm Structure Survey 2010 reports remarkably lower numbers with 3% certified organic area if total UAA and 1.3% organic farms of total number of farms (EUROSTAT 2012a, p. 55).

Table 14: Organic Farming in EU-27, 2011

EU Member State	Organic agricultural land		Organic producers	
	Area (ha)	Share of total agricultural land (%)	Producers	Share of total agricultural holdings 2010 (%)
Austria	542,553	19.7	21,575	14.4
Belgium	59,220	4.3	1,274	3.0
Bulgaria	25,022	0.8	978	0.3
Cyprus	3,575	2.4	732	1.9
Czech Republic	460,498	10.8	3,904	17.1
Denmark	162,173	6.1	2,677	6.4
Estonia	133,799	14.8	1,431	7.3
Finland	188,189	8.2	4,114	6.4
France	975,141	3.6	23,135	4.5
Germany	1,015,626	6.1	22,506	7.5
Greece	309,823	3.7	21,274	2.9
Hungary	124,402	2.9	1,433	0.2
Ireland	54,122	1.3	1,400	1.0
Italy	1,096,889	8.6	42,041	2.6
Latvia	184,096	10.4	3,484	4.2
Lithuania	152,305	5.7	2,652	1.3
Luxembourg	3,720	2.8	96	4.4
Malta	23	0.2	9	0.1
Netherlands	47,205	2.4	1,672	2.3
Poland	609,412	3.9	23,430	1.6
Portugal	201,054	5.8	2,434	0.8
Romania	229,948	1.7	9,471	0.2
Slovakia	166,700	8.6	365	1.5
Slovenia	32,149	6.6	2,363	3.2
Spain	1,621,898	6.5	32,195	3.3
Sweden	480,185	15.4	5,508	7.7
United Kingdom	638,528	4.0	4,650	2.5
Total European Union	9,518,234	5.4	236,803	2.0

Source: Willer et al. (2013); EUROSTAT (2013d)

Constrains for the introduction of organic farming

Future continuation of the organic farming growth in the EU is depending from the following factors:

- *Mindset*: Organic farming demands a major change from conventional production systems, influenced by the opinion of colleagues, rural communities and overall societal recognition.
- *Follow-up for farm operation*: Investment and changes connected with a conversion to Organic Farming will only be undertaken if the continuation of the farm is secured.
- *Adaptive research and demonstration efforts*: Key problems in organic crop production are nutrition supply, weed and pest management. Principles of OF need to be adopted to specific farming situations. Beside adaptive research, chances of learning from farmer to farmer are important.
- *Advisory services*: An adequate extension and/or consultancy all over the country is important for solving conversion problems and developing organic crop production adopted to the operating conditions of farms.
- *Infrastructure for market access*: The separated market and labelling for organic food makes it necessary to find new customer, the opening of new marketing channels.
- *Organic product prices*: Profitability of organic farming is dependent from the price premium of organic products. Increasing demand for organic food, well balanced with enhanced organic production, is a precondition. Future overall development of agricultural product price has also an influence.
- *Continues support scheme*: Support schemes in the frame of agro-environmental programmes are a relevant incentive for the expansion of Organic Farming. The design of the second column of the CAP after 2013 and the funding on the national level will influence the attractiveness of Organic Farming.
- *Coexistence with GM crop production*: The use of GMOs is prohibited in organic production. Future development GM crop cultivation, coexistence regulation and performance influence the successful application of coexistence.

4.1.5. Agroforestry

Agroforestry systems (Table 15; extensive description and discussion in Marohn 2009) are land use systems which combine deliberately interplanted annual crops and trees in different storeys. Agroforestry works on the basis of a *set of reasoning and design principles* rather than fixed planting schemes. The aim is to explore productively a variety of ecological niches while minimising inter- and intraspecies competition. Another key principle is to establish and maintain a tight nutrient cycle, including nitrogen fixation by means of leguminous trees and nutrient pump function by means of deep rooting trees (Meyer 2010). According to their main managed components, agroforestry systems can be classified into (Marohn 2009):

- *Silvoarable systems*: annual crops and shrubs/trees;
- *Silvopastoral systems*: pasture or cut fodder with animals and trees;
- *Agrosilvopastoral systems*: trees, crops, pasture/cut fodder and animals.

Innumerable systems and designs, adopted to local conditions, are possible, ranging from extensive to intensive systems, from spatially differentiated to sequential systems, and from home gardens to systems with export cash crops.

Indigenous and local knowledge is an important source of information when it comes to species selection, tree-site matching, preferred uses and cultural acceptance, and non-governmental organisations (NGOs) play an important role in agroforestry projects.

Statistic data about extent and distribution of agroforestry system are not available. But the importance of agroforestry can be measured by two indirect indicators. The first approach describes the *tree cover on agricultural land*, based on the following data (Zomer et al. 2009, p. 4):

- Global land use: Spatial data layers exist which classify any pixel as agricultural or some other land use.
- Global tree cover: Remotely sensed data has been interpreted to give estimates of % tree cover in a pixel.

Table 15: Agroforestry – overview

Criteria	Components / outcomes
Key principles	> Deliberately interplanted annual crops and trees > Design adopted to local conditions
Main objectives	> Productive use of a variety of ecological niches > Minimising inter- and intraspecies competition > Establishing and maintaining a tight nutrient cycle > Prevention of soil degradation > Better water retention and preservation > Diversification of production
Modifications in crop production	> Selection of adequate tree varieties > Diversified crop rotations > Green manure, animal manure and compost > Nitrogen supply with legumes or leguminous trees > Tree pruning and management
Strengths	> Crop quality and yields can be increased > Higher resilience of production system > Diversification of economic activities > Maintenance of ecological and aesthetical important landscapes
Weaknesses	> Potential competition for light, water, nutrients > Limitations for mechanisation > Higher workload > Establishing of new marketing channels
Area of implementation	> Worldwide: approx. 375 - 425 million ha, around 20% of arable land > EU-27: only partial data available
Relevant crops	> Cereals, oilseed, fodder crops, vegetables, grape vine (as annual crops)

Source: Based on Meyer (2010); STOA (2009)

Result of the analysis is that 17% of the global agricultural land (3.744.544 km²) involves agroforestry, based on the assumption that agricultural land with more than 30% tree cover is classified as Agroforestry (Zomer et al. 2009, p. 14). The data sets and methods used in this analysis have a number of limitations. An important limitation is that information on the tree configuration in the landscape is lacking so that a 50% tree cover in a 1 km x 1 km pixel can vary from 50% treeless crop land and 50% dense forest to 100% trees and crops fully integrated at the finest scale (Zomer et al. 2009, p. 42).

The second indicator describes the *regional distribution of major agroforstery farming systems*, based on the farming system approach (Dixon et al. 2001). Summing-up the land area of these farming systems in Sub-Saharan Africa, South and East Asia (including the Pacific region) and Latin America (including the Caribbean), tree-based agricultural systems in the developing world cover around 425 million hectares (Dixon et al. 2001). The spatial mapping and figures of farming systems is insofar a simplification as they describe the dominant system and don't specify the real extent of Agroforestry systems.

Impacts of agroforestry systems

The principle advantages of silvoarable systems are in yield diversification and the production of short-term returns on land while the planted trees are still young. In order to minimise potential negative interactions between trees and crops, careful selection of combinations of trees and associated crops which have positive interactions is essential. Research has shown that mixed systems can be more productive than monocropping, especially if the trees obtain resources that would otherwise be unavailable to crops, thereby reducing the need for agrochemicals (Eichhorn et al. 2006).

Various case studies illustrate that, in the long run, agroforestry systems often prove to be superior to conventional monocropping systems in terms of common economic indicators (e.g., for Bangladesh: Rahman et al. 2007). Agroforests have the ability to mitigate economic and ecological risks, which can be strongly interrelated (Meyer 2010). On a macroeconomic level, Agroforestry products (e.g., coffee, cacao) account for a significant share (up to 50 per cent) of agricultural export earnings in many developing economies (STOA 2009, p. 17).

Important ecosystem services of agroforestry systems are in both tropical and temperate regions (Jose 2009):

- Enhancing and maintaining long-term soil fertility and productivity;
- Biodiversity conservation;
- Improved air and water quality;
- Carbon sequestration.

Agroforestry in the EU

Silvoarable systems have formed key elements of European's landscapes throughout historical times. In many cases they represent formerly widespread traditional systems in decline and a number have already become extinct or exist only in a threatened state. The combinations of trees and crops employed by European farmers are immensely varied. In terms of their major productive trees, five categories of silvoarable systems can be recognised in Europe (Eichhorn et al. 2006):

- Olive tree systems
- Fruit tree systems
- Timber tree systems
- Oak tree systems
- Fodder tree systems

In general, the form and structure of systems are determined by light limitation in northern Europe and by water limitation in the Mediterranean. Systems have often mixed functions. For example, fruit trees (e.g. walnut, pear) are often dual-purpose and produce a timber end-product. Important examples of fruit tree systems in northern Europe are (Eichhorn et al. 2006):

- The "pré-vergers" in northeast France: areas of low-density fruit tree plantations and grazing land),
- The central European system of "Streuobst": tall trees of different types and varieties of fruit which are dispersed on croplands, meadows and pasture in a rather irregular association.

Olive trees are continuous element of the Mediterranean landscape, are typically planted in rows, although they can also be irregularly scattered, and are intercropped with cereals, vegetables and fodder crops, and sometimes grape vines.

In part of Mediterranean countries, the landscape is defined by the presence of scattered oaks, forming contiguous arable and pastoral associations. The most characteristic example is the "dehesas" of southwest Spain and Portugal which is the dominant agroforestry system in Spain and probably the largest such system in Europe (Table 16). The ground beneath the trees is periodically sown with cereals, fodder crops or sunflower, or is used as pasture. The lengths of rotations vary from 2 to 12 years. The minimum size of an operational "dehesas" estate is thought to be around 400 ha (Eichhorn et al. 2006).

Official statistical data on agroforestry in the EU are not available. Available data on the extent of silvoarable systems stem from varied sources of information[36] (Table 16). In north-western Europe (e.g. Germany, the Netherlands, United Kingdom), silvoarable agroforestry no longer has a significant role in the agrarian economy. The extent of intercropped fruit orchards of northwest Europe was strongly reduced and is now largely silvopastoral (Eichhorn et al. 2006).

Silvoarable agroforestry remains of importance in many regions of the Mediterranean. The greatest diversity of silvoarable systems is found in Greece, where a large variety of combinations of trees and crops exist. These are generally characterised by small plot area. Silvoarable agroforestry remains widespread in Italy and Spain, but is restricted to the more marginal areas, especially olive grove intercropping and "dehesas" (Eichhorn et al. 2006).

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[36] Data on silvoarable systems were collected in the EU-funded project „Silvoarable Agroforestry For Europe (SAFE)" which included the seven Member States France, Greece, Germany, Italy, Spain, the Netherlands und the United Kingdom.

Table 16: Extant of silvoarable agroforestry systems in some European countries

Silvoarable system	Country	Extent (ha)	Component trees
Olive tree systems	Italy	20,000	Olive, other fruit trees
	Spain	15,000	
	France	3,000	
	Greece	650,000	
Fruit tree systems	Germany	~ 400,000	"Streuobst"
	France	15,000	Walnut
	France (Languedoc-Roussillon)	?	Peach + vegetables
	United Kingdom (Kent)	?	Apple, cherry
	Greece	?	Pear, walnut, figs
Timber tree systems	Italy (North)	12,500	Poplar
	Italy (Central + South)	10,000	Walnut, Hazel
	France	6,300	Poplar
	Greece	7,600	Walnut
Oak tree systems	Italy (Central + South, Sardinia, Sicily)	180,000	Oak, pear
	Greece (South + West)	29,600	Oak
	Greece (North + Central)	1,470,000[37]	Oak
	Spain (West + Southwest)	2,300,000[37]	Oak
	Portugal	869,000[37]	Oak
Fodder tree systems	Italy (Sicily)	20,000	Carob
	Greece (Crete)	7,900	Carob

Source: Synthesised from Eichhorn et al. (2006)

In a modelling exercise, Reisner et al. (2005) identified target regions for silvoarable agroforestry in Europe. The analysis shows that the investigated five commercial tree species (walnut, wild cherry and

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[37] Less than 10% of arable cereal land is estimated to be containing scattered oaks.

poplar for temperate Europe, Italian stone pine and holm oak for Mediterranean Europe) could grow productively in silvoarable agroforestry systems on 56% of the arable land throughout Europe. Overlaying potential productive tree growth areas with the arable land that is considered as environmental risk area yielded the final target regions. They were found to make up about 40% of the European arable land.

Constraints for the introduction of agroforestry

For the last decades, basic causes for the decline of silvoarable agroforestry systems across Western Europe and the retreat to more marginal regions in Mediterranean countries are (Eichhorn et al. 2006):

> Scattered trees in arable landscapes impede mechanised agriculture and have been deliberately removed or were damaged by machinery.
> Reduction of manpower in agriculture limited the commercial viability of labour-intensive Agroforestry systems.
> Consolidation of fragmented land holdings into larger single farms and fields removed boundary trees and reduced the scope of landscape diversity.
> Research, extension and practice for increased yields were focused on maximising productivity through monocropping systems.
> EU fruit quality norms and market demands for standardised fruits favour their production in intensively managed orchards.
> The subsidy regime of the Common Agricultural Policy (GAP) led to a reduction of crop associations by favouring single crop systems.
> Regulations separate agricultural and forestry land use into distinct categories so that Agroforestry systems fall between the two types of land use.

Many of these points represent continuing constraints for the maintenance and new establishing of silvoarable agroforestry systems in Europe. Additionally, potential barriers are:

> Deficient knowledge about economic valid and locally adopted design of agroforestry systems;
> Available knowledge about tree-site matching, upbringing, management, etc. of cultivated trees;
> Extended time scale for agroforestry research, with very few studies yet available of complete cycles from tree planting to harvest;
> Missing compensation for establishment costs and reduced returns in the initial period after establishment;
> Availability of marketing opportunities for multiple products in relative low quantities.

4.1.6. Integrated crop-livestock production systems

In industrialized agriculture, crop production and husbandry are increasingly separated. This separation of crop and livestock production takes place on farm level (specialised farms), regional level (diversification of specialised crop and livestock production areas) and international level (e.g. feed production in Latin America for the EU livestock production).

In contrast, integrated crop-livestock systems have been a foundation of agriculture for hundreds of years. Aim is an intentional integration that reflects a synergistic relationship among the components of crops, livestock and/or trees and that this synergistic relationship enables enhanced productive, economic, social and environmental sustainability of the system (FAO 2010a, p. 9).

Table 17: Integrated crop-livestock production systems – overview

Criteria	Components / outcomes
Key principles	> Crop and livestock production within a co-ordinated framework on farm > Farm-internal use of crop products as feed and of waste products as fertilizers > Diversification of farm production and economics
Main objectives	> Synergistic relationship between the production components > Maintenance and improvement of soil fertility > Improving of crop yields and quality > Lower production costs > Reducing of economic risks through diversification
Modifications in crop production	> Modification of crop rotation > Integration of fodder plants > Fertilizing with organic fertilizers
Strengths	> Improvement of soil organic matter and soil fertility > Greater soil water storage capacity > Yields can be increased > Higher resilience of production system > Diversification of economic activities
Weaknesses	> Availability of adequate feed to sustain animals and of organic resources to maintain soil fertility > Interconnection of management decisions in integrated crop-livestock systems due to the cyclic relation between organic resources, livestock, land and crops > Necessary improvement of manure application to reduce nutrient losses
Area of implementation	> Worldwide: approx. 1.1 billion ha arable rainfed cropland, 0.2 billion ha irrigated cropland, 1.2 billion ha grassland; around 50% of total agricultural land > EU-27: around 20 million ha, 12% of arable land
Relevant crops	> Cereals, fodder crops, oilseeds, roots and tubers, sugar crops

Source: Own compilation

Integrated crop-livestock production describes farming systems in which livestock and crops are produced within a co-ordinated framework (Table 17). Traditionally, and still in many instances, this framework comprises a farm unit, although integration can also take place on an area-wide basis that may involve some specialisation. In many mixed systems, the waste products of one component serve as a resource for the other: manure from livestock is used to enhance crop production, whilst crop residues and by-products feed animals. Other forms of mixing take place where grazing under fruit-trees keeps the grass short, or where manure from pigs is used to feed fish in a pond (Keulen, Schiere 2004).

Mixed farming systems utilize about half of all land used for livestock production systems: around 2.5 billion hectares, of which 1.1 billion are arable rainfed cropland, 0.2 billion hectares is irrigated cropland

and 1.2 billion hectares grassland. These farming systems make the largest contribution to the world livestock production with just over 50% of the meat and 90% of the milk production worldwide (CAST 1999, p. 28). Mixed production systems generate close to 50% of the world's cereals and most of the staples consumed by poor people: 41% of maize, 86% of rice, 66% of sorghum, and 74% of millet production (FAO 2010a, p. 1). The regional distribution and total land area of mixed farming systems in developing countries was estimated, based on a global livestock production classification system and a mapping approach (Table 18).

Integrated crop-livestock systems in developing countries can be distinguished in two classes which differ in their degree of intensification. Mixed intensive systems have higher population density, high agro-ecological potential (especially through irrigation), good links to markets, and use some purchased inputs regularly. A typical example is the western Indio-Gangetic plains. Mixed extensive systems have medium population density, moderate agro-ecological potential, are largely dependent on rain-fed agriculture, and use few purchased inputs. These systems can be found in much of Sub-Sahara Africa, especially in the West and South (Tarawali et al. 2011).

A mix of crops and livestock helps feed many people in the world, and it supports farmers obtain an income in different agro-ecologies. In India, the Green Revolution in crop production was accompanied by a White Revolution in dairying which emerged from very different approaches to development, but productivity growth is closely linked combination of crops and livestock at farm level (Basu, Scholten 2012). Sustainable intensification of mixed crop-livestock systems will require to give equal importance to both the technological dimension as well as innovative and practical approaches encompassing institutional, policy and market solutions that work for those engaged in crop-livestock systems at ground level (Tarawali et al. 2011). Mixed farming systems are seen as the main avenue for intensification of food production in Asia (Devendra 2002).

Table 18: Total land area of mixed crop-livestock systems by global regions (km²)

Region	Rainfed arid / semi-arid	Rainfed humid / sub-humid	Rainfed high-land / tempe-rate	Irrigated arid / semi-arid	Irrigated humid / sub-humid	Irrigated high-land / tempe-rate	Total mixed systems	Percen-tage of total agricul-tural area (%)
Latin America	953,460	2,826,721	1,450,042	168,779	92,560	135,558	5,627,120	27.7
East Asia	75,150	391,500	1,999,020	9,075	165,125	1,194,650	3,834,520	35.0
South Asia	1,216,470	422,425	82,375	1,196,275	316,550	8,400	3,242,495	73.9
South-east Asia	11,725	1,296,150	105,250	3,100	463,225	14,225	1,893,675	39.8
Central Asia	129,975	1,700	875,300	97,500	3,550	310,200	1,418,225	35.1
Sub-Sahara Africa	3,410,903	2,328,326	793,957	109,906	817	9,931	6,653,840	27.6
West Asia and North Africa	1,096,168	40,875	424,077	708,401	10,662	108,074	2,388,257	19.4
Total	6,893,851	7,307,697	5,730,020	2,293,036	1,049,489	1,781,038	25,055,131	31.0

Source: Kruska et al. (2003)

In spite of the importance of integrated crop-livestock farming, however, there is a trend in teaching, research and policy towards work on specialised farming. That trends associates with mindsets that focus on commodities and parts rather than on mixed farming as interconnected wholes, also called complex adaptive systems (Schiere et al. 2006).

Impacts of integrated crop-livestock systems

The environmental nitrogen problem in the EU is related to recent segregation of animal and crop production, and specialisation and intensification on farms and in regions. It was proposed that a long-term solution could be a re-allocation and re-integration of main agricultural systems. Potential chances are seen especially for the integration of production of vegetables, root and tuber crops with animal production in mixed farming systems which should be located on the better soils of the EU (Oomen et al. 1998). Two experimental prototype mixed farms in the Netherlands have shown that nitrogen surplus and nitrogen losses to the environment could be reduced (Latinga et al. 2004).

Cultivated forages as an important part of mixed farming have received much less attention from plant scientists than have cereal, fruit, and vegetable crops. As a result, great potential exists to improve yield and quality of forage crops through development of new varieties and cultural practices (CAST 1999, p.56).

Overall benefits of crop-livestock integration in developing countries are (IFAD 2013):

> Maintenance and improvement of soil fertility(with physical, chemical and biological soil recuperation);
> Greater soil water storage capacity, mainly because of biological aeration and increase in the level of organic matter;
> Weed control by animals grazing vegetation (Devendra, Thomas 2002b);
> Improving of crop yields and quality;
> Better economic performance, through product diversification, reduced production costs (especially by fertilizer from livestock operations instead of unaffordable chemical fertilizers), and higher yields and improved quality;
> Small stock act as cash buffer and large ruminants as a capital reserve (Devendra, Thomas 2002a);
> Animal traction by large ruminants, especially in areas with high land to population ratio (Devendra, Thomas 2002b);
> Ecological improvements, through less pesticide use and better soil erosion control;
> Social benefits, through the reduction of rural-urban migration and the creation of new job opportunities in rural areas.

Integrated crop-livestock systems in the EU

In the EU-27 together, 20.15 million ha are used by mixed crop-livestock farms, or 11.7% of the total agricultural area. 1.5 million farms are such mixed farms, which accounts for 12.6% of all holdings in the EU (EUROSTAT 2013a). Czech Republic, Slovakia, Poland and Lithunia have the highest percentage of mixed farms on total agricultural area[38].

Constrains for the introduction of integrated crop-livestock systems

The rate of change to integrated crop-livestock systems in developed countries will be restricted by the absence of structure and management skills for livestock in specialised arable areas and the large capital requirements for change. However, this can be overcome by establishing mixed farming between farms, with systems at a regional level. They are characterised by intensive cooperation between two or more specialised farms, each producing crop or animal products (Lantinga et al. 2004).

In a worldwide view, important constraints are (IFAD 2013):

> Generally low nutritional values of crop residues;
> Availability of adequate feed to sustain animals and of organic resources to maintain soil fertility;
> Interconnection of management decisions in integrated crop-livestock systems due to the cyclic relation between organic resources, livestock, land and crops;
> Necessary improvement of manure application to reduce nutrient losses;
> Established dependency on chemical fertilizers in high input production systems;
> Adaptation of integrated systems depend on access to credit, technology and knowledge;
> Livestock management needs to safeguard water, in regard to livestock water demand and contaminations from manure and urine.

4.1.7. Conclusions

Based on the detailed analysis of each crop production system, their contribution to main objectives of sustainable intensification and their relevance and potential in farming systems worldwide and of Europe are discussed in this summing up chapter.

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[38] The number of holdings and agricultural area for mixed farming in EU Member States is documented in Annex C.

The main objective of adapting production inputs site-specifically within a field is to improve input use efficiency (Table 19). Therewith, precision agriculture does not contest per se high external input agriculture and specialisation in crop production, but intends to make crop production more effective and environmental-friendly. In contrast, the central objective of the other discussed crop production systems is to improve the site specific yield potentials, with maintenance and enhancement of soil fertility in the centre. They imply deeper changes in crop production systems: diversified crop rotations, plant associations, green manure and permanent organic-matter soil cover, and/or integration of crop and livestock production. Better input efficiency is in these cases a consequence of the main objective.

Table 19: Contribution of different crop production systems to main objectives of improved crop production

Crop production system	Higher yields	Better input efficiency	Improved site specific yield potential
Precision agriculture	(+)	+	(+)
Conservation agriculture	+	+	+
System of rice intensification	+	+	(+)
Organic farming	+ / -	+	+
Agroforestry	(+)	+	+
Integrated crop-livestock systems	(+)	+	+

Legend: +high relevance; (+) restricted relevance, - no relevance
Source: Own assessment

Precision agriculture leads in most cases only to restricted yield increases, in a range up to 5%. High potentials for increasing yields are reported for conservation agriculture and for the system of rice intensification in developing countries. A mixed picture exists for organic farming, with high yield increases for low external input systems in developing countries and yield reductions in developed countries. Mixed systems of agroforestry and integrated crop-livestock farming have also the potential to be more productive.

The crop production systems are not suitable for all farming systems worldwide (Table 20). *Precision agriculture* as a high-tech approach is only feasible for industrialized and intensive farming due to investment costs, complexity of the technology and required knowledge. Nonetheless, single techniques and non-digital approaches such as micro-dozing of nutrients or varied fertilizer application based on visual observation can be applied in small-scale farming of developing countries and extensive farming systems of Europe. In the last decades, *conservation agriculture* has mainly spread in large-scale farming of developing and transition countries, but also in some intensive small-scale farming systems of developing countries. In Europe, the introduction is lagging behind. Still unutilized potentials for Conservation Agriculture exist in context of extensive farming. The *System of Rice Intensification* is an innovation of developing countries, applied both in extensive and intensive crop production systems. *Organic farming* in Europe is concentrated on extensive farming systems. The barriers for introducing Organic Farming in intensive farming systems are relatively high so that conversion rates are low. Organic Farming principles can improve extensive small-scale farming in developing countries, but certification requirements are a barrier to enter international markets for organic food. *Agroforestry systems* are broadly used in different small-scale farming systems of developing countries. In Europe, they have declined in extensive farming systems and vanished in intensive farming systems. *Integrated crop-livestock farming systems* are of high relevance in developing countries and in extensive European farming systems. Intensive crop farming in Europe is characterised by their separation from livestock production, but new chances are seen by regional cooperations on a regional level.

Extensive small-scale semi-subsistence farming partly uses agroforestry systems and they are often integrated crop-livestock farms (Table 21). The implementation of conservation agriculture or organic farming is difficult due to the lack of resources. Precision farming is not applicable.

Extensive farming in less favoured areas has high potentials to apply conservation agriculture and organic farming due to relative low conversion costs. Traditional agroforestry system survived in a number of less favoured areas so that there are chances for revival of agroforestry. Beside the important extensive livestock systems based on grazing, integrated crop-livestock farming is also of relevance. The chances to introduce precision agriculture as a high-tech approach are rather small.

Table 20: Current relevance of crop production systems in different farming systems worldwide

Crop production system	Extensive small-scale farming developing countries	Intensive small-scale farming developing countries	Industrialized large-scale farming developing / transition countries	Extensive farming Europe	Intensive farming Europe
Precision agriculture	-	-	+	(+)	+
Conservation agriculture	(+)	+	+	-	(+)
System of rice intensification	+	+	-	-	-
Organic farming	+	(+)	(+)	+	(+)
Agroforestry	+	+	(+)	(+)	-
Integrated crop-livestock systems	+	+	-	+	(+)

Legend: +high relevance; (+) restricted relevance, - no relevance

Source: Own assessment

Mixed farming systems are per definition integrated crop-livestock farms. Mixed farming is a key element of many organic farms so that the conversion potential is in many cases high. Conservation agriculture and agroforestry can be integrated in mixed farming, restricted by the already existing complexity of the farm operation. The relevance of precision farming is low due to the relative high investment costs and learning requirements.

Intensive larger-scale crop farming has a high potential to apply precision agriculture with the aim to enhance input efficiency and to reduce production costs. In this farming system, the maintenance and enhancement of soil fertility is of high importance, for which conservation agriculture is a suitable approach. The competitiveness of organic farming is relatively low and higher conversion rates can only be expected when new marketing channels with attractive price premiums can be opened up. Silvoarable agroforestry has vanished in intensive crop farming due to the impediment of highly mechanised cultivation and unfavourable economic incentives. Barriers for an introduction of modern agroforestry systems are relatively high. Over the last decades, larger-scale crop farms have abandoned livestock production. The potential for a reintegration of crop and livestock production is restricted by the absence of structure and management skills for livestock in specialised crop farms and the large capital requirements for change.

In the case of *large-scale corporate farming*, economics of scale are favourable for the introduction of precision agriculture. Barriers for implementation can be missing management skills. Conservation agriculture is a relevant approach for maintenance and enhancement of soil fertility. Mindset and lower profitability for diversified crop rotations can be barriers. Large-scale corporate farms have successfully conversed to organic farming. Conversion implies a major change in farm organisation and marketing. Agroforestry is at odds with the mechanisation and specialisation. In parts, corporate farms are integrated crop-livestock operations. Integration of livestock production in corporate farms specialised on crop production is restricted due to high investments and missing management skills for livestock.

Table 21: Current relevance of crop production systems in different farming systems of the EU

Crop production system	Extensive small-scale, semi-subsistence farming	Extensive farmingin less favoured areas	Medium intensive, mixed farming systems	Intensive, larger-scale crop farming	Large-scale corporate farming
Precision agriculture	-	(+)	(+)	+	+
Conservation agriculture	(+)	+	(+)	+	+
Organic farming	(+)	+	+	(+)	(+)
Agroforestry	+	+	(+)	-	-
Integrated crop-livestock systems	+	(+)	+	-	(+)

Legend: +high relevance; (+) restricted relevance, - no relevance

Source: Own assessment

Despite all differences between the crop production systems in regard to approach and implementation chances, some important trends in the frame of sustainable intensification can be identified (see also Meyer et al. 2011):

> *Increasing differentiation of crop management*: Instead of single technologies or fixed technology packages, crop management gets increasingly adopted to local conditions and spatial variability in the field, with the perspective of plant to plant variability.

> *Higher complexity of management concepts*: Increasing incorporation of production input variables and natural production conditions in the planning and execution of crop production.

- *Agriculture gets more knowledge-intensive*: Knowledge-intensive agricultural practices result from increasing differentiation and higher complexity of crop management approaches. There are two distinctive ways: One way is to incorporate knowledge in technology and computerized decision support and making systems (Precision agriculture). The other way is to strengthen knowledge and adaptation capacities of farmers in participatory approaches. Latter is combined with more and more appreciation of local and indigenous knowledge.
- *Shift to system approaches*: System-based principles and approaches with local adaptations and integration try to address the specific agro-ecological, social and economic conditions of farmers at their specific locations.
- *Mainstreaming of agro-ecological approaches*: The preservation and enhancement of the natural production potentials of agriculture (such as soil fertility, water conservation, biodiversity sustainment) get more and more recognised as a central part of sustainable intensification. They are essential to stabilize achieved high yield levels in favourable areas, to realise more of existing yield potentials, and to increase the resilience of farming systems.
- *Combination bottom-up and top-down approaches*: Local adaptations of policies and actions are seen as highly important for sustainable intensification of agricultural production systems. But a piecemeal of local projects and actions is not enough for national and cross-boarder scaling up. National and European policies and international knowledge exchange are essential to promote and spread local activities.

4.2. Technologies and practices for sustainable intensification

In this chapter, existing and emerging technologies and practices which are part of the production systems will be discussed in more detail, as additional step in the analysis. The technologies and practices for sustainable intensification are classified in such for

- overall crop production management,
- soil management,
- water management,
- nutrition management,
- pests, diseases and weed control management.

The placement of technologies and practices in these management categories results from their main objective, although many technologies and practices aim simultaneously at different objectives.

4.2.1. Practices and technologies of crop production management

In this category are subsumed practices which change the crop production programme of a farm. In most cases, the crop production on a specific field is changed over more than one year. Alley cropping is presented as an example for the multitude of agroforestry systems. Changes have always a number of objectives, aiming on improvements of soil fertility, water availability, nutrition supply and pest management. Impact should be increased yields and productivity. Table 22 gives an overview on the relevance of crop production management practices and technologies for different EU farming systems, which will be discussed in the following sub-chapters.

Table 22: Relevance of different practices and technologies of crop production management in different farming systems of the EU

Practices and technologies	Extensive small-scale, semi-subsistence farming	Extensive farmingin less favoured areas	Medium intensive, mixed farming systems	Intensive, larger-scale crop farming	Large-scale corporate farming
Rotation	+	+	+	(+)	+
Green manure / cover crops	-	+	(+)	+	+
Seed mixtures	+	+	(+)	(+)	(+)
Intercropping	+	(+)	(+)	+	+
Alley cropping	-	(+)	(+)	+	+
Contour farming	-	+	+	+	+
Buffer strips	-	(+)	(+)	+	+
Bench terraces	+	+	(+)	-	-

Legend: +high relevance; (+) restricted relevance, - no relevance

Source: Own assessment

Rotation

Crop rotation is the alternation of crops with different characteristics, cultivated on the same field during successive years. Crop rotation is the opposite to monoculture which is the cultivation of the same species year after year in the same place (Florentin et al. 2011, p. 71).

Objectives of crop rotation are (Florentin et al. 2011, p. 72):
- Better control of pests and diseases of crops;
- Better weed control;
- Increased crop yields;
- More abundant and lasting soil cover;
- Maintaining and/or increasing soil organic matter content;
- More uniform and stable extraction of nutrients, favouring equilibrium in the soil profile, by alternating root systems with different characteristics and depths;
- Improvement of soil structure, facilitating crop development;
- Greater biological diversity;
- Diversification of risks related to production and price variations;
- Better distribution of work throughout the year;

In the EU, crop rotations typically last 3 to 5 years in conventional agriculture, and 5 to 10 years in organic agriculture. Rice in Northern Italy, cotton in Greece, Spain and Portugal are exclusively cultivated in monoculture. Only restricted areas of monoculture in grain cultivation (e.g., maize) can be found (Mudgal et al. 2010, p. 7, 11). In the last decades, key drivers for simplified rotations were

- Breeding of high-yielding varieties restricted to a small number of crop species, which become the main revenue in crop production;
- Availability of chemical inputs (fertilizer, pesticides), which reduced the dependency from crop rotation services such as soil fertility, weed and pest control;
- Mechanisation in different stages, from which resulted larger fields and which contributed to simplification of rotations;
- Concentration of market demand on a restricted number of crops (e.g., maize, wheat) and reduced demand for legumes;
- Support measures targeted on some corps, in the CAP of the past.

Since 2003, mechanisms of cross-compliance were introduced in the CAP. They link the granting of CAP payments to the respect of mandatory standards in the fields of environment, public, animal and plant health, and animal welfare. Farmers have to maintain their land in Good Agricultural and Environmental Condition (Mudgal et al. 2010, p. 15). These regulations had no significant impact on the diversity of crop rotations in the EU. The Greening component in the proposal of the Commission for the past 2013 CAP foresees also new regulations for rotations. This part of the proposal is discussed controversial, and partly regarded as insufficient (e.g., Heinrich et al. 2013).

Diversified crop rotations are a key principle of conservation agriculture, organic farming and agroforestry, and are important in integrated crop-livestock production systems. Rotation is of relevance in all discussed European farming systems (Table 4.12). The more specialised a farm is, the more restricted is the number of crops in their rotation. Therewith, rotations are specifically restricted in intensive, larger-scale crop farming. The composition of crop rotations depends on

- Agronomical and agro-ecological conditions (e.g., climatic and soil conditions);
- Types of farming system;
- Economic context (e.g., market prices and opportunities);
- Social context (e.g., education, advisory services, neighbours)
- Agricultural and environmental policies;
- Technological advances.

In recent years, some important focuses of research on crop rotation were:

- Energy crops;
- Organic farming;
- Integrated pest management.

Diversified crop rotations should be based on the following principles (Mudgal et al. 2010, p. 8):

- Deep-rooted crops should rotate with shallow-rooted ones, to optimise the exploration of nutrients in soil. Moreover, deep-rooted crops help to maintain the soil structure.
- Spring-sown and autumn-sown crops should rotate, to break cycles of weeds, pests and pathogens.
- A crop should not follow a closely related species, to avoid common weeds, pests and pathogens.
- Crops with a high level of ground cover, which maintain weeds at a low level, should rotate with crops where weeds are controlled mechanically (hoeing).
- Crops that leave significant amounts of residue should be included.
- Legumes should be included, in order to help fix atmospheric nitrogen in the system.
- Elements of intercropping and/or cover crops should be introduced, which support to cover the ground and protect soil structure, and which provide habitat to fauna, including beneficial insects.

Green manure / Cover crops

Green manure or cover crops are plants that are grown in order to provide soil cover and to improve the physical, chemical, and biological characteristics of soil. Green manure may be sown independently or in association with crops. Green manures represent fresh green plant matter (often of legumes) that is ploughed in or turned into the soil to serve as manure, or used as organic matter cover over the soil. Green manure can either be grown in situ and incorporated in the field or grown elsewhere and brought in for incorporation in the field, in which case it is referred to as green-leaf manuring. There are limits to the use of green manuring under arid conditions because of the additional water requirement (Roy et al. 2006, pp. 121-123; Florentin et al. 2011, p. 9).

In general, green manure/cover crops are used to pursue the following objectives (Florentin et al. 2011, p. 9):

- Provide soil cover for no-tillage (reduces water evaporation and soil temperature, and increases water infiltration);
- Protect soil from erosion;
- Reduce weed infestation.
- Add biomass to soil (in order to accumulate soil organic matter, add and recycle nutrients, feed soil life);
- Improve soil structure;
- Promote biological soil preparation;
- Reduce pest and disease infestation.

Green manures can add substantial amounts of organic matter and N as well as other nutrients. The bulk of the N input through leguminous green manures comes from biological nitrogen fixation. Using rice culture as an example, this can range from 50 to 200 kg N/ha (Roy et al. 2006, p. 122).

A meta-analysis of experiments (mainly from the USA) with fertilizer-intensive cash crop systems had the result, that the yields under non-legume cover crop management were not significantly different from those in the conventional, bare fallow systems, while nitrate leaching was reduced by 70% on average. Relative to yields following conventional N-fertilization, the legume-fertilized crops averaged 10% lower yields. However, yields under green manure fertilization were not significantly different relative to conventional systems when legume biomass provided 110 kg N per ha. On average, nitrate leaching was reduced by 40% in legume-based systems relative to conventional fertilizer-based systems (Tonitto et al. 2006). Beside higher yields, cover crops reduce soil erosion by wind and water, increase infiltration of rainfall in the soil and reduce evaporation from soil surface, and suppress weeds (NRC 2010, p. 94 ff.).

Cover crops are more and more integrated in European crop production management, especially in the context of conservation tillage (Chapter 4.2.2.). Successful use of cover crops necessitates managing the entire crop rotation. Cover crops / green manure is a key element of conservation agriculture and of importance in organic farming.

Seed mixture

The concept of seed mixtures has been developed to increase the robustness of yield against environmental stresses. The architecture of plant root systems is important for the acquisition of resources and specific root structures are best adapted to particular abiotic stresses. Root structure can therefore be limiting to growth and yield in variable environments, as the plant will only be adapted to one particular set of conditions. Genotypes that develop a deep tap root are best adapted to drought-prone environments, particularly when the drought occurs late in the season during development of reproductive structures (e.g. corn). Genotypes that result in roots close to the surface of the soil mobilise effectively immobile nutrients and are generally better adapted to low phosphorus environments (Lynch 2007; Royal Society 2009, p. 26).

For example, genotypes of beans selected for high capacity to acquire phosphorus often have shallow roots (Lynch 2007). This can cause problems for crops in water-scarce environments, where deep roots can be advantageous for water scavenging. Mixtures of genotypes can be planted to buffer the crop yield against combinations of stresses. In such mixtures, it is possible that shallow rooted genotypes may also benefit from the extraction of water by deep rooters in the community (Caldwell, Richards 1989). Development of these techniques requires an understanding of the different crop ideotypes that are helpful to combat different environmental stresses (Royal Society 2009, p. 26).

Variety mixtures can provide functional diversity that limits pathogen and pest expansion (Finckh et al. 2000). Mixtures must be compatible in terms of agronomic and quality characteristics. The usefulness of mixtures for disease management has been well demonstrated for rusts and powdery mildews of small grain crops. Yield increases of 1-5% are often provided by cultivar mixtures in the absence of substantial disease, with larger increases when disease is of significance. Yield benefits can sometimes be substantially greater in larger scale use than in small experimental plots. Higher yield stability is an additional benefit of seed mixtures (Mundt 2002). In traditional agricultural systems, mixtures within wheat, barley and potatoes are widely used in the Andes, cereals and legumes in Pakistan, and rice in Africa and Asia (Wolfe 1985). Cultivar mixtures are seen as an important tool for crop management also in industrialised countries (e.g., in Europe), which should be appropriately evaluated within the context of the local agriculture and through direct interaction with farmers (Mundt 2002). Organic farmers are especially open-minded to the use of seed mixtures. In the more intensive European farming systems, a rethinking of the pure variety concept is demanded.

Intercropping

Intercropping is the growth of two or more crops in the same field during a growing season. Intercropping usually intends to make good use of the different growth habits of the combined crops so that there is complementary in the use of time (different maturity periods), space (different root or canopy arrangements) and/or crop physiology (Francis 1986; Altieri 1995; Meyer 2005). An example of intercropping is the combined cultivation of legumes and cereals. As in any bio-diverse ecosystem, the interaction between complementary plants enhances the overall stability of the system, including a significant resilience against pests, diseases and weeds, and the mitigation of abiotic stress. The practice of intercropping can increases soil porosity and supports organic carbon and nitrogen cycles; there are indications of positive effects on soil biology and biodiversity too. Studies highlight the variability in net returns for a number of intercrops (Louwagie et al. 2009). Intercropping systems require a greater degree of management skills (NRC 2010, p. 104).

Intercropping systems are common in subsistence, small-scale farming in tropical areas (NRC 2010, p. 103). In Europe, intercropping is generally associated with small-scale, semi-subsistence farming, and organic agricultural systems. Intercropping has potential in both industrialised and non-industrialised agriculture. The approaches are often based on traditional practice and with more research into interactions between plants they could be more widely adopted (Royal Society 2009, p. 27).

Alley cropping

Alley cropping (or hedgerow intercropping) is an agroforestry practice (see Chapter 4.1.5.) in which perennials (preferably leguminous trees) or shrubs are grown simultaneously with an arable crop. Alley cropping is broadly defined as the planting of rows of trees and/or shrubs (single or multiple) at wide spacing, creating alleyways within which agricultural crops or horticultural crops are produced. The trees may include valuable hardwood veneer or lumber species, nut or other specialty crop trees/shrubs, or desirable softwood species for wood fiber production. The purpose is to enhance or add income diversity (both long and short range), reduce wind and water erosion, improve crop production, improve utilization of nutrients, improve wildlife habitat or aesthetics (USDA Forest Service 1999). In tropical areas, alley cropping retains the basic restorative attributes of the bush fallow through nutrient recycling, fertility regeneration and weed suppression and combines these with arable cropping. Normally, the trees are pruned before planting the crop. The cut leafy material is spread over the crop area to provide nutrients for the crop. In addition to nutrients, the hedges serve as windbreaks and reduce soil erosion.

In recent years, alley cropping systems are analysed in Europe in regard to the production of high grade wood (e.g., Spieker et al. 2009) and as a bioenergy resource (e.g., Gruenewald et al. 2007). Alley cropping systems contribute to improve microclimatic conditions on arable farm land and therefore may enhance the crop yield stability in sensitive regions. This is supported by a more efficient use of water and improved nutrient use efficiency. Ecosystem services are positively affected by alley cropping in various ways. But further research and more practical experiences with different implementations of alley cropping are needed to allow a more accurate adoption to specific site conditions (Quinkenstein et al. 2009).

Field shelterbelts as windbreaks (e.g., hedgerows) increase yields of field and forage crops throughout the world. The increases are due to reduced wind erosion, improved microclimate, snow retention and reduced crop damage by high winds. Crops differ in their responsiveness to shelter. Winter wheat, barley, rye, millet, and mixed grasses and legumes appear to be highly responsive to protection (Kort 1988).

Contour farming

Contour farming involves activities, such as ploughing, furrowing and planting, carried out along contours instead of up and down the slope. It aims at creating detention storage in the soil surface horizon and slowing down the rate of run-off. Contour farming thus increases the soil's infiltration capacity, may have positive effects on organic carbon content, and results in controlling water and tillage erosion. However, climate, soil type, slope aspect and land use should be taken into account when judging the suitability of this practice (Louwagie et al. 2009). Many development projects train farmers to lay out ploughed or hoed ridges on the contour (Tripp 2006).

Buffer strips

Buffer strips (filter strips, field borders, windbreaks, grassed waterways, riparian buffers, etc.) at the edge of arable lands can significantly reduce (by 70-90 %) the volume of suspended solids, nitrates and phosphates transported by agricultural run-off to water bodies, and pesticide loads. Depending on the type, they can reduce wind erosion and contribute to biodiversity and aesthetics of the landscape (Louwagie et al. 2009, p. X; NRC 2010, p. 82).

On the economic side, buffer strips lead to a reduction of cultivated area, and causes costs for their establishment (seeding, planting) and maintenance (mowing). Certain national agri-environmental measures include compensations to farmers for these costs. Depending on local conditions, they may replace or reduce the need for other nature restoration activities (Louwagie et al. 2009).

Bench terraces

The construction of various types of terrace is one of the major techniques for soil conservation in hillside farming. This technology is of ancient origin. Its large labour requirements have often been met by community organisation or state coercion. However, there are also approaches that are more amenable to local initiative and work without stone walls (Tripp 2006, p. 23).

Bench terraces consist of a series of (nearly) levelled platforms built along contour lines, at suitable intervals and generally sustained by stone walls. Terracing has a particularly beneficial effect on the soil's infiltration rate and capacity and thus on controlling water erosion. However, the high maintenance required, coupled with the high cost of labour and the significant changes in the socio-economic structure of the agricultural population over the last decades in Europe, has led farmers to abandon terraces. In turn, many authors report adverse effects of terracing once they are badly maintained or even abandoned (Louwagie et al. 2009). As far as terraces are maintained that takes place in extensive production systems.

In some mountain areas of the Mediterranean region (e.g., north-eastern Spain), increasing vineyard terracing is being observed. These new terraces are not constructed in the traditional manner using human labour and stone walls. Land terracing accelerated after the introduction of the EU Council Regulation policy for vineyards' restructuring (EC Regulation No. 1227/2000), in 2000, which subsidizes up to 50% of the construction cost. Soil conservation practices are largely ignored in the construction phase, resulting in high negative environmental and landscape impacts (Cots-Folch et al. 2006).

4.2.2. Practices and technologies of soil management

Major starting point for improved soil management is tillage, the soil preparation before seeding. A number of changed tillage systems is available (Table 23). They aim to preserve soil structure and soil organic matter. The practices and technologies for permanent soil cover und for supply of organic matter, "feeding" the soil and presented in chapter 4.2.1, are supplementary and represent major contribution to the improvement of soil fertility.

Tillage has long been used by farmers to loosen soil, make a seedbed and control weeds. Tillage embraces all soil operations using plough, harrow and other farm tools or mechanical implements for seedbed preparation that aim at creating soil and environmental conditions for seed germination, seedling establishment and crop growth. Intensive tillage systems leave little crop residue cover on the soil (Kassam et al. 2009).

Since the sustainability of a soil's productive capacity depends on the influence of the soil biota on soil aggregate re-formation, the soil aerating effects of undue tillage can accelerate the rate of biotic activity and the consequent more-rapid oxidation of soil organic matter. If the mean rate of soil's physical degradation exceeds the mean rate of its recuperation due to the soil biota, its penetrability by water, roots and respiration gases diminishes, productivity declines, and runoff and erosion increases. The soils which are most vulnerable to tillage-stimulated rapid loss of soil organic matter are those of coarse texture and where the clay fraction is dominated by low-activity clays. Such soils (e.g., ferralsols, cambisols) are widely distributed in the tropics and subtropics (Kassam et al. 2009).

Table 23: Relevance of different practices and technologies of soil management in different farming systems of the EU

Practices and technologies	Extensive small-scale, semi-subsistence farming	Extensive farmingin less favoured areas	Medium intensive, mixed farming systems	Intensive, larger-scale crop farming	Large-scale corporate farming
Conservation tillage	+	+	+	+	+
Ridge tillage	-	(+)	(+)	(+)	(+)
No-tillage	(+)	+	+	+	+
Subsoiling	-	-	(+)	+	+
Variable rate liming	-	(+)	(+)	+	+

Legend: +high relevance; (+) restricted relevance, - no relevance

Source: Own assessment

Conservation tillage

The primary aim of conservation tillage is to reduce tillage operations typically associated with intercrop soil or seedbed preparation with the aim to reduce soil erosion. Conservation tillage has been defined as any tillage sequence that reduces the loss of soil or water relative to plough-till; often it is a form of non-inversion tillage that retains a protective layer of mulch (Kassam et al. 2009).

In organic farming, reduced tillage raises specific challenges because the use of herbicides is prohibited (NRC 2010, p. 92). While US organic farming researchers have focused on no-tillage and vegetative mulch created by killed cover crops (e.g., by blade roller), European organic farming researchers have concentrated on reduced tillage through the reduction of tillage depth or the application of non-inversion tillage practices. The results of reduced tillage experiments in organic farming obtained so far in Europe clearly demonstrate the superiority of these systems to conventional plow systems with respect to soil biology and soil fertility. However, there are major challenges and research gaps inhibiting more widespread application of reduced tillage in European organic farming systems (Carr et al. 2011; Mäder, Berner 2011). With the new European regulation on pesticide use and introduction of IPM principles (Chapter 4.2.5), there is a need also for conventional non-inversion tillage systems to redesign cropping systems (Melander et al. 2013).

Data on conservation tillage in the EU-27 (Table 14) show great differences in uptake between Member States. Therewith, not all areas with soil erosion or soil fertility problems (Chapter 3.2.1. and 3.2.3.) are addressed.

Strip-till (or ridge tillage)

Strip-till is a conservation system that uses a minimum of tillage. Each row that has been strip-tilled is usually about 20–25 cm wide. It normally involves a tillage operation in the autumn that clears residue in the target seed zone, places soil in a ridge to aid drying and soil warmth to facilitate seeding at a later date, and may or may not include fertilizer placement. The ridges are alternated with furrows protected by crop residues. A second operation at seeding time places seed (and usually additional fertilizer) in the ridged seed zone. This type of tillage is performed with special equipment (Kassam et al. 2009).

Ridge tillage has positive effects on moisture-holding capacity, physical properties of soil and soil fertility maintenance (including organic carbon content) and biological activity and thus on water erosion and nutrient run-off. Evidence suggests that ridge tillage can be an economically viable alternative to conventional tillage with higher net returns and lower economic risk. Ridge tillage has only been studied in experiments in most parts of Europe (Louwagie et al. 2009, p. IX; NRC 2010, p. 86 ff.).

No-till (or no-tillage)

No-till refers to growing crops from year to year without disturbing the soil through tillage. The crop is planted directly into a seedbed that has not been tilled since the previous seedbed. The maximum amount of crop residue is retained on the surface, and weeds are controlled by chemicals, by residue mulch, by using an aggressive cover crop, or by a combination of these methods. Soil-disturbing activities are limited only to those necessary to plant seeds, place nutrients and condition residues (Kassam et al. 2009). No-tillage is a key principle of conservation agriculture (Chapter 4.1.2.).

Overall, rates of zero tillage (no tillage) are low in the European Union. The EUROSTAT Farm Structure Survey 2010 reports rates a little bit over 5% of the arable land for Denmark, Estonia, Spain, Romania and Finland (Table 14).

Subsoiling

Subsoiling involves loosening deep hardpans in soils (below the ploughing depth), thereby improving the soil's infiltration rate and root penetration. The harder soil layer just below the cultivation depth is the result of "traditional" mouldboard tillage and the use of increasingly larger and heavier machinery for field operations. In particular, subsoiling has a beneficial effect on infiltration rate and capacity, but shows variable effects on nutrient cycling. The effects of subsoiling are influenced by many other parameters such as a combination of practices, type of crop and soil, (micro-)climate, period of soil cultivation, etc. (Louwagie et al. 2009, p. IX, 73). Subsoiling is often combined with the introduction of conservation tillage or no-tillage.

Variable rate liming

Lime adjusts soil chemistry (pH of soil). Site-specific lime management is seen as one of the most feasible strategies for variable rate applications. On-the-go soil sensors are available, but difficult to implement. They can provide accurate pH information at a rather low cost. After collecting pH values, however, data have to be translated into a lime application map to identify an adequate lime input. So far, few results concerning yield increases or lime saving due to variable rate liming have been published (Jensen et al. 2012).

4.2.3. Practices and technologies of water management

Enhancing water use efficiency is an increasing issue in industrialized agriculture of developed countries, and holds the key to tackling water scarcity and food security issues in smallholder agricultural systems of developing countries. The present system of irrigation water supply and water allocation requires adjustments to avoid over-irrigation and inefficient use of water, and to address the twin-issues of waterlogging and salinity to maintain crop productivity (Hanjra, Qureshi 2010).

Adequate arrangements of rotation, cover crops / green manure, seed mixtures, intercropping and/or agroforestry systems contribute to water preservation and availability in soils. In this chapter, practices / technologies for improved management of “blue” and “green” water are to be discussed.

In irrigation systems, “blue” water use can be reduced during transport from the source to the farm, typically along canals (conveyance efficiency), from the farm gate to the field (distribution efficiency), and during application to crops (application efficiency). For example, conveyance efficiency can be increased by lining canals; distribution efficiency can be enhanced by lining and maintaining on-farm canals; and application efficiency can be increased by using more sophisticated irrigation technologies, such as drip or sprinklers.

Increasing agricultural output per drop of water depleted will allow more food to be grown with less water. There is tremendous potential for water productivity gains in irrigated and rain fed areas. This will require a combination of agronomic, economic and social interventions – including crop breeding (chapter 5.), soil and fertility management (chapter 4.2.2.), irrigation water management, and water rights and allocation of blue water supplies. In rain fed areas, mitigation of dry spells with on-farm water harvesting or supplemental irrigation can potentially triple water productivity in much of sub-Saharan Africa (SIWI 2004).

Drip irrigation

Drip irrigation involves dripping water onto the soil at very low rates (2-20 litres/hour) from a system of small diameter plastic pipes fitted with outlets called emitters or drippers. Water is applied close to plants so that only part of the soil in which the roots grow is wetted, unlike surface and sprinkler irrigation, which involves wetting the whole soil profile. With drip irrigation water, applications are more frequent (usually every 1-3 days) than with other methods and this provides a very favourable moisture level in the soil around the plants. Drip irrigation is most suitable for row crops (e.g., vegetables), tree and vine crops where one or more emitters can be provided for each plant. Generally only high value crops are considered because of the high capital costs of installing a drip system (FAO 1988).

One of the main problems with drip irrigation is blockage of the emitters. All emitters have very small waterways ranging from 0.2-2.0 mm in diameter and these can become blocked if the water is not clean.

Thus it is essential for irrigation water to be free of sediments. If this is not so then filtration of the irrigation water will be needed. Drip irrigation is particularly suitable for water of poor quality (saline water). Dripping water to individual plants also means that the method can be very efficient in water use. For this reason it is most suitable when water is scarce (FAO 1988).

Shifting to drip irrigation has been the greatest strategic improvement inwater-use efficiency and energy savings over the past three decades. Most orchards and vineyards in the USA are converting to these systems, and a broad range of annual horticultural crops.The application tubes are placed in close proximity to the tree or vine of crop plants, and water is applied as needed, monitored by a host of newly engineered moisture and plant stress-sensing devices. Impacts of drip irrigation are significant savings in water, energy, fertilizer, and pesticides use (NRC 2010, p. 114).

Deficit irrigation

Regulated deficit irrigation regimes, in which plants are mildly stressed to activate stress tolerance mechanisms, increase water use efficiency of the plant (Davies et al. 2002). They can be combined with methods such as mulching the soil. With deficit irrigation, very high water use efficiencies can be achieved. Deficit irrigation can also be used as an effective tool for growth regulation, reducing vegetative growth in favour of reproductive development in fruit crops and thereby enhancing "crop yield per drop of water" and crop quality (Royal Society 009, p. 27).

Only some crops are suitable for regulated deficit irrigation, and growers need to have a clear understanding of crops' responses to water stress during different stages of growth and development and under different environmental conditions (NRC 2010, p. 115).

Rainwater Harvesting

Collecting, storing and concentrating precipitation at different scales, the so called water harvesting, is an ancient technique dating back 4,000–5,000 years. In the last two decades, it is under revival in response to the importance of rain-fed crop production and the escalating water scarcity (Falkenmark et al. 2001, as quoted in IAASTDT 2009b: 134). Eighty percent of the agricultural land worldwide is under rain-fed agriculture, with generally low yield levels (Rockström et al. 2003).

Rainwater harvesting (RWH) (extensive description and discussion in Balke 2009) compromises the collection, filtration and storage of local rainwater and surface run-off and decentralised water distribution systems for domestic consumption, livestock and irrigation. The water can be stored in the soil for the (immediate) water supply of plants, or in cisterns and reservoirs for later use. Various techniques can be applied to reflect local conditions (climate, morphology, soil, etc.) (Meyer 2010).

RWH methods can be applied in any climatic zone with a water deficiency, but existing installations are often not well maintained and need to be improved. The introduction or improvement of RWH systems should be combined with adequate agricultural production methods (e.g., Conservation Agriculture) in order to increase water use efficiency and soil fertility. Examples demonstrate that the crop yield of rainfed cultivation can be doubled and more using RWH techniques (Balke 2009). Compared with other methods of producing usable water (e.g., deep wells), RWH techniques are much cheaper and easier to maintain, making them favourable for resource-poor small-scale farmers (STOA 2009, p. 15).

In Burkina Faso, Mali and Niger, formerly degraded and abandoned lands were transformed with the adoption of traditional water-harvesting techniques, for example, tassas in Niger and zaï in Burkina Faso. Farmers are digging planting pits (also known as zaï) across the rock-hard plots. Their innovation was to increase the depth and diameter of the pits and then add organic matter, such as manure, to the bottom of the basins, with the aim to improve soil fertility, water retention and yields. Another innovation based on traditional farming practice was the building of stone contour bunds to harvest rainwater. The total area in Burkina Faso rehabilitated over the past three decades is estimated to be between 200,000 and 300,000 hectares (IAASTDT 2009c, p. 18; Reij et al. 2009).

Rainwater harvesting areas are not well mapped and few statistics are available at the national or regional level. From the AQUASTAT FAO databases, data exist only for Tunisia (898,000 ha), Egypt (133,000 ha), Iran (40,000 ha), and Lebanon (500 ha) (IAASTDT 2009b, p. 71).

4.2.4. Practices and technologies of nutrition management

Adequate supply of crop nutrients in accordance to the nutrient demand of the plant is a cornerstone for realising yield potential. Efficient nutrient uptake by the plant depends on good soil structure and root development, soil microflora – mycorrhizae are particularly important because most plant species acquire P via mycorrhizal symbioses – and sufficient soil moisture content. Achieving better crop nutrition requires maintenance/improvement of soil fertility and novel strategies for more precise plant nutrient management tailored to the technologies, dynamics and spatial scales relevant to the farming systems. Options for improved nutrient management include the handling of mineral (synthetic) fertilizers and organic fertilizers.

Variable rate fertilization

Site-specific nutrient management, also called variable rate technology, is discussed for all major crop nutrients (Chapter 3.2.3.). Site-specific nitrogen management is most advanced and used in practice. This is of high relevance because current nitrogen management strategies for worldwide cereal production systems are characterized by low nitrogen use efficiency (NUE) (Shanahan et al. 2008).

Two approaches for site-specific nitrogen application are available (Ferguson et al. 2007):

- Predictive approach with management zones,
- Reactive approach with sensor-based in-season crop monitoring.

In the predictive approach to nitrogen management, time and amount of nitrogen application is prescribed prior to planting. It relies primarily on the use of multiple layers of spatial information to generate yield potential zones within fields. Management zones are field areas possessing homogenous attributes in landscape and soil condition. Significant in-field variability is necessary precondition. The first step in this approach is to collect spatial data. Soil maps, topography, electrical conductivity sensors, crop yield maps and producer experience can be used. In the next step, the spatial information has to be transformed in yield potential zones, also called management zones. The simplest approach is to draw manually boundaries on a map, based on visual comparison. Alternatively, potential yield zones can be generated by special software. Once yield potential zones have been created, soil samplings from these zones are analysed for soil organic matter, pH, phosphorus, potassium and nitrate. Nitrogen application rates for the zones are calculated from expected yield, soil organic matter and residual nitrate (Ferguson et al. 2007). Disadvantage is that weather-mediated variability in crop nitrogen demand is not integrated (Shanahan et al. 2008).

Reactive nitrogen management allows the timing and amount of nitrogen to be regulated by assessment of crop nitrogen status for top-dressing applications. Crop plant leaves or canopy measurements have long been known to serve as an indicator for nutrient needs. Simplest approach is a visual assessment using calibration plots (Shanahan et al. 2008). Present sensor systems measure either chlorophyll concentration in the leaves, total area of the leaves or crop resistance against bending. None of the methods analyses the nitrogen status directly. Either the development of the canopy, the chlorophyll concentration within the leaves or both phenoma together are used as indicators of the nitrogen supply. These indicators can also depend on diseases, on deficiencies of other nutrients or lack of water. Therewith, a healthy crop well supplied with other nutrients and water is a precondition (Heege et al. 2008). For adjusted nitrogen rates, unique crop and/or region-specific algorithms are applied. They require in-season sensor readings from non-N-limiting reference strips, knowledge of planting dates, and regional yield limits. They need refinements in order to account for management, soil and climate differences (Shanahan et al. 2008).

Profitability of variable rate approaches is still discussed and dependent from many factors. An analysis of a farm in Western Australia had the outcome that only around a third of the fields generated an additional economic payoff when managed with variable rate technology in comparison to uniform management. Variation and starting level of soil fertility were the most important factors for profitability (Lowes, Robertson 2011). On-farm yield experiments in the USA have found clear evidence of site-specific corn yield response to applied nitrogen fertilizer. However, the yield response was not consistent across years under rainfed farming conditions. In consequence, opinion is that profitable ex ante site-specific nitrogen recommendations cannot be developed with the information currently available (Liu et al. 2008). Results from experiments with wheat in the USA indicate no economic advantage of variable rate nitrogen application with sensor systems (Biermacher et al. 2009; Boyer et al. 2011). Studies with management zones could not demonstrate significant economic benefits over uniform applications (Dobermann, Cassmann 2002). Dobermann and Cassmann (2002) propose that site-specific nutrient management should be more broadly defined as the dynamic, location-specific management of nutrients in a particular cropping season. Following this approach, field- and season-specific fertilizer applications in irrigated rice in different Asian countries had caused higher yields, increased average nutrient uptake and nitrogen use efficiency, and higher profitability (Dobermann et al. 2002; Peng et al. 2010).

Integrated nutrition management

In the past two decades, it has been increasingly recognized that plant nutrient needs in many countries can best be provided through an integrated use of diverse plant nutrient resources. Integrated nutrient management (INM) enables the adaptation of the plant nutrition and soil fertility management in farming systems to site characteristics, taking advantage of the combined and harmonious use of organic, mineral and biofertilizer nutrient resources to serve the concurrent needs of food production and economic, environmental and social viability. In the last two decades, FAO has been engaged actively in the development of INM and has focused global attention on the need for large-scale adoption of INM, through its field projects, expert consultations and publications (Roy et al. 2006).

The basic concept underlying INM is the maintenance or adjustment of soil fertility (soil productivity) and of optimal plant nutrient supply for sustaining the desired level of crop productivity. The objective is to accomplish this through optimization of the benefits from all possible sources of plant nutrients, including locally available ones, in an integrated manner (Roy et al. 2006, p. 145).

INM aims to improve the production capacity of a farm through the application of external plant nutrient sources and amendments, and the efficient processing and recycling of crop residues and on-farm organic wastes. It should empower farmers by increasing their technical expertise and decision-making capacity. It also promotes changes in land use, crop rotations, and interactions between forestry, livestock and cropping systems as part of agricultural intensification and diversification (Roy et al. 2006, p. 146).

During the adoption of INM, special attention should be given to sources of nutrients that may be mobilized by the farmers themselves (manures, crop residues, soil reserves, biological nitrogen fixation, etc.). Minimization of losses and replenishment of nutrients from both internal and external sources are of major interest. While INM strives for the integrated application of diverse inputs, in this concept the use of organic sources does not replace the use of mineral fertilizers. Although the effects of organic inputs go beyond the nutritional aspects, by contributing to improving soil physical properties and to a better efficiency of fertilizer use, the recycling of organic materials are seen as not sufficient to fully replenish the nutrients that are removed by crop harvests (Roy et al. 2006, p. 148).

Integrated nutrient management has strong connections to conservation agriculture, system of rice intensification, organic farming, agroforestry systems and integrated crop-livestock systems. The variable rate application of fertilizers in the frame of precision agriculture can be an important element of INM. The concept of INM is in principle applicable in all European farming systems; major barriers are the required knowledge about complex agronomic decision making and the availability of the proposed different nutrient resources.

Organic fertilizers

Organic sources of nutrients are derived principally from substances of plant and animal origin. These sources cover manures made from cattle dung, excreta of other animals, other animal wastes, rural and urban wastes, composts, crop residues and even green manures (Roy et al. 2006, p. 119). Green manures have already be discussed in chapter 4.2.2. As another example, compost is descript here.

Although many organic waste products can be added directly into the soil, most of them have a better soil-improving effect and are a more effective source of nutrients after their decomposition through the composting process. The resulting mixed and improved products following decomposition are termed compost. Compost can be defined as an organic manure or fertilizer produced as a result of aerobic, anaerobic or partially aerobic decomposition of a wide variety of crop, animal, human and industrial wastes. Composting has a long tradition almost everywhere in the world (Roy et al. 2006, p. 125). Compost play a role in organic farming.

Limitations for using compost technologies by small-scale farmers in developing countries are the relative large amounts of required biomass, competition with other uses for that biomass (e.g., fuel, fodder), and the labour necessary to prepare and manage the compost pit and transport the compost. Composting has received relatively little attention so far in low-input agricultural projects in developing countries (Tripp 2006, p. 28).

4.2.5. Practices and technologies of pest, disease and weed control management

Significant reductions of crop yields can result from competition from weeds, pest and diseases, that represents biotic stress to plants. A broad spectrum of practices and technologies is available to mitigate biotic stress, ranging from crop protection chemicals (pesticides) to natural defence strategies.

Beside explicit crop protection strategies, several approaches such as cover crops, mulches and alley cropping (Chapter 4.2.1.) make important contributions to weed control and reduction of pest pressure. Additionally, the use of adopted and/or resistant cultivars plays a major role.

Integrated pest management

Integrated pest management (IPM) aims to maintain pest infestations below economically acceptable levels. Principle is to encourage natural control of pests by anticipating pest problems and preventing pests from reaching economically damaging levels. All appropriate techniques should be used such as enhancing natural enemies, plant pest-resistant crops, adapting cultural management, and using pesticides judiciously (Oerke, Dehne 2004). It stays in contrast to preventive and calendar-based application of pesticides, and the attempt to eradicate pests.

IPM programs have been established in various crops around the world and have proven their suitability in developed and developing countries. IPM is successfully practised in perennial and annual crops in temperate and tropical conditions for the control of all pest groups, especially insect pests and fungal pathogens (Oerke, Dehne 2004).

In industrialized agriculture, IPM paid in the past special attention to field-based management and market-driven decision making. This generated an incentives dilemma for farmers: selecting IPM activities for individual fields on the basis of market-based economics versus selecting IPM activities best applied regionally that have longer-term benefits, including environmental benefits, that accrue to the broader community as well as the farmer. Financial incentives available to farmers from agro-environmental programs may offer opportunities to overcome the incentives dilemma when advanced IPM strategies are used regionally (Brewer, Goodell 2012).

Box 3

EU pesticide regulation

A common regulation of evaluation, marketing and use of pesticides was introduced with the Directive 91/414/EEC. Therewith was initiated a Community-wide review for all active substances used in plant protection products. The review programme started slowly because harmonised technical requirements had to be set first. Decisions started to be taken in 2001, and the review process was finalised in March 2009. Of around 1,000 active substances on the market in at least one Member State before 1993, 26% corresponding around 250 substances, have passed the harmonised EU safety assessment. The majority of substances have been removed from market because dossiers were either not submitted, incomplete or withdrawn by industry. About 70 substances failed the review and have banned, because the evaluation did not show safe use with respect to human health and the environment (DG SANCO 2009). With replacing regulation 1107/2009/EC, new criteria for the approval of active substances have been introduced and in the future safeners, synergists and adjuvants will also require approval (EC 2009). Overall aim is to minimise the hazards and risks to health from the use of pesticides and to reduce the levels of harmful active substances including through substituting the most dangerous with safer (including non-chemical) alternatives. It is expected that with re-evaluation approvals for several active substances will not be renewed in the EU (Hillocks 2012).

In same year, a new EU regulation on sustainable use of pesticides was approved (Directive No 2009/128/EC). Member States have to set up National Action Plans which will set objectives to reduce hazards, risks and dependence on chemical control for plant protection. Enhanced protection of the aquatic environment from pollution by pesticides is demanded to contribute to the achievement of the objectives of the Water Framework Directive. Low pesticide-input farming is to promote and all farms in the EU must implement principles of Integrated Pest Management (IPM) for their crop protection activities (Hillocks 2012).

In developing countries, many IPM projects and programmes work with the concept of farmer field schools (FFS) in which farmers become acquainted with agro-ecological principles in a social learning context, through hands-on learning. Prominent examples come from irrigated rice production in Asia. At the time of the Green Revolution, rice farmers' use of insecticides hat increased rapidly, because the technology package allowed more frequent planting, some of the new varieties were more susceptible to pest attacks, and in government programmes pesticides were part of the extension package. The increasing pesticide use became counterproductive by destroying natural enemies. With IPM, the complex and effective regulation mechanisms of irrigated rice system were better used, and the pesticide use rates lowered and the timing of application improved (Tripp 2006, p. 35).

The new EU pesticide regulation requires from all farmers that pesticides are used within an Integrated Pest Management framework by 2014 (see Box 4.1). It is expected that the combined effects of the pesticides review, additional legislation to protect water quality and the IPM legislation will trigger fundamental changes in farming systems (Hillocks 2012).

The EU supported the ENDURE Network between 2007 and 2010 with funding under the European Commission's 6th Framework Programme. Activities were designed to create a Network of Excellence for IPM-related research, support a multi-disciplinary research programme and ensure the results of this research reached all interested stakeholders. This was followed by PURE (Pesticide use-and-risk reduction in European farming systems with IPM) launched in March 2011. PURE involves partners in 10 European countries, builds on research initiated in ENDURE, focussing on a systems approach, examining the role of larger spatial (cropping system) and temporal (multiyear) scales in crop protection (Hillocks 2012).

The ENDURE project worked out that IPM can be considered as a continuum, ranging from optimisation of pesticide use within the current crop protection system to substitution via the adoption of non-chemical strategies and to more radical redesign of production systems by acting on crop rotations, landscape and varieties. The path of an individual farmer along the IPM continuum is a gradual process and ranges over a number of years. This process involves changing the way in which farmers and their neighbours assess their work. Lasting collective dynamics involving farmers, advisers and researchers are key to the emergence of robust and far-reaching transitions. Therefore, it is proposed that policies designed to promote IPM should include support to farmer and farmer-advisor groups (Lamine et al. 2010).

Agro-ecological approaches

Agro-ecological approaches intend to conserve or introduce biodiversity in agro-ecosystems and to increase beneficial biotic interactions in agro-ecosystems. The aim is a drastic reduction in pesticide use while keeping crop pest and disease damage under control (Alterieri et al. 2012; Malézieux 2012; Médiène et al. 2011; Ratnadass et al. 2012). Agro-ecological approaches are a key element of advanced integrated pest management approaches.

Crop rotation (Chapter 4.2.1.) with non-host plants is the first general agronomic rule to avoid soil-borne diseases. Crop diversity with non-host effects at the field level over time disrupt the life cycle of soil-borne pest and diseases (Ratnadass et al. 2012). Crop diversity on a field and landscape scale can influence, via concentration of host-plants and favouring of natural enemies, the pest dynamics and disease epidemics (Malézieux 2012).

Pest deterrence or repellence effects involve mainly bottom-up and trophic effects which can be used to control anthropod pests. The pests are deterred or repelled from the main crop by "push" stimuli which can be delivered by intercropping with non-host plants with deterrent or repellent attributes that are appropriate for the target pest. On the other side, trap crops can be plants that divert pest pressure from the main crop because they are more attractive. A thorough understanding of the behaviour of the pest and the way it is effected by the relative attractiveness of the trap crop compared with the main crop, the ratio of main crop and trap crop and its spatial arrangement is crucial to the success of this strategy (Ratnadass et al. 2012).

This can be combined to "push-pull" systems. An example is the "push-pull" system for maize cultivation in East Africa which combines knowledge of agro-biodiversity and the chemical ecology of these stem borers with Striga management. The maize field is first surrounded by a border of the forage grass Pennisetum purpureum (Napier grass). Napier grass is more attractive to the moths than maize for laying their eggs, therewith providing the trap crop and "pull" aspect. The Napier grass produces a gum-like substance which kills the pest when the stem borer larvae enter the stem. Napier grass thus helps to eliminate the stem borer in addition to attracting it away from the maize. In addition, rows of maize are intercropped with rows of the forage legume silverleaf (Desmodium uncinatum). Desmodium releases semiochemicals which repel the stem borer moths away from the maize, the repellent and "push" aspect. An alternative repellent intercrop is molasses grass (Melinis miniutiflora) which also produces semiochemicals that attract natural enemies of the stem borer moth. Desmodium has the additional benefit of fixing atmospheric nitrogen, thereby contributing to crop nutrition. Remarkably, Desmodium has also been found to be toxic to African witchweed (Striga), so has an additional crop protection benefit (Cook et al. 2007; Hassanali et al. 2008; Pickett et al. 2010; Royal Society 2009, p. 29). Therewith, mixed cropping, also called companion cropping, is seen as an important tool for intensifying agricultural production systems (Pickett et al. 2010).

In some soils, disease suppressiveness is probably due to the activity of soil microbiota since suppressive soils consistently have higher populations of actinomycetes and bacteria than do soils conducive to diseases. The addition of organic material increases the general level of microbial activity, and the more microbes there are in the soil the greater are the chances that some of them will be antagonistic to pathogens (Ratnadass et al. 2012).

At the landscape level, habitats made of perennial and annual vegetation located outside cropped fields, may play a role as a source of pollen and nectar for adults of pest parasitoids, and can act as "banks" for parasitoids and predators of crop pests by increasing their population on the alternative prey they shelter before the arrival of the target pest on the neighbouring crop (Ratnadass et al. 2012).

Ecological weed management, also called cultural weed control, can be described as adjustment or modification to the general management of the crop or cropping system that contributes to the regulation of weed populations and reduces the negative impact of weeds on crop production. Key principles of cultural weed control are a reduced recruitement of weed seedlings from the soil seedbank, an alteration of crop-weed competitive relations and a gradual reduction of the size of the weed seedbank. Cultural control strategies need to consist of a combination of measures, resulting in increased systems complexity which hampers large-scale implementation. Tailoring cultural weed management strategies to the needs and skills of individual farmers would be an important step forward (Bastiaans et al. 2008).

Biological pest control

The introduction of natural enemies or the sterile insect technology are well established approach to control or eliminate pest, especially invasive pests. Challenges from native and exotic pests require national policy that promotes biological control. These approaches are strongly connected with responsibility of national plant quarantine services (Popp et al. 2013).

Two new strategies involving the release of GM insects have been proposed: population suppression and population replacement. Proponents of GM insects consider them to be a tool to complement existing control methods. But development and use of GM insects is highly controversial. Environmental NGOs such as Greenpeace suggest that GM insects could have unintended and wide ranging impacts on the environment and human health due to the complexity of ecosystems and the high number of unknown factors, making risk assessment difficult. Guidelines for the release of GM insects are currently lacking, and several international efforts are currently under way to draft them (POST 2010).

Biopesticides (also known as biological pesticides) are pest management agents based on living micro-organisms or natural products. They can be derived from such natural materials as animals, plants, bacteria, and certain minerals. Microbial pesticides consist of a microorganism (e.g., a bacterium, fungus, virus, or protozoan) as the active ingredient. Microbial pesticides can control many different kinds of pests, although each separate active ingredient is relatively specific for its target pest. For example, there are fungi that control certain weeds, and other fungi that kill specific insects. Biochemical pesticides are naturally occurring substances that control pests by non-toxic mechanisms. Additionally, they include semiochemicals, such as insect sex pheromones that interfere with mating, as well as various scented plant extracts that attract insect pests to traps (EPA 2012).

Currently the most widely used biopesticide is Bacillus thuringiensis (Bt) which is an insecticide with unusual properties that make it useful for pest control in certain situations. Bt is a naturally occurring bacterium common in soils throughout the world. Several strains can infect and kill insects. Because of this property, Bt has been developed for insect control. In recent years, there has been tremendous renewed interest in Bt. Several new products have been developed, largely because of the safety associated with Bt-based insecticides (IUPAC 2012).

About 1,400 biopesticide products are sold worldwide. At present, there are 68 biopesticide active substances registered in the EU and 202 in the USA. The EU biopesticides consist of 34 microbials, 11 biochemicals and 23 semiochemicals. The biopesticide products represent just 2.5% of the total pesticide market (Chandler et al. 2011). Today, biopesticides are mostly use in covered crops, but there are significant opportunities for their use in other sectors (Blum et al. 2010). Global sales of biopesticides are estimated to total around US$ 1 billion, still small compared to the US$ 40 billion in the worldwide pesticide market (Popp et al. 2013).

In the EU, biopesticides are regulated in the same way as synthetic chemical pesticides, requiring the same data sets. However, several draft documents have been produced to give guidance on the actual requirements when applied to biopesticides (IUPAC 2012). Development and registration of a biopesticide needs in average 3 to 6 years and an investment of US$ 15-20 million, compared with 10 years and US$ 200 million for synthetic chemical pesticides (Popp et al. 2013).

The new EU pesticide regulation (see Box 3) gives a specific status to non-chemical and natural alternatives to conventional chemical pesticides and requires them to be given priority wherever possible. Biopesticides should generally qualify as low-risk active substances which are granted initial approval for 15 years rather than the standard 10 years. A reduced dossier can be submitted for low-risk substances but this has to include a demonstration of sufficient efficacy (Chandler et al. 2011).

Barriers for a broader adoption of biopesticides are (Chandler et al. 2011; Popp et al. 2013):

- Niche market products: Many biopesticides have high levels of selectivity. This is of great in terms of not harming other natural enemies and wildlife, but it means that biopesticides are niche products with low profit potential.
- Small- to medium-sized biopesticide companies: In contrast to the large agrochemical companies, the biopesticide sector is composed mostly of small- to medium-sized enterprises, for which it is difficult to fully and comprehensively fund research and development, field development and provide the marketing services required to make a successful biopesticide company.
- Fixed costs: Because conventional chemical pesticides are used so widely, the fixed costs associated with them are spread over many users. Potential adopters of biopesticides face large fixed costs of adoption that will only decrease once the technology is used more widely.
- Farmers' risk aversion: Because conventional pesticides have been the mainstay of crop protection for over 50 years, there is a wealth of experience that gives farmers confidence in their effectiveness. the more limited evidence base and practical experience with biologically based IPM technologies create uncertainty for farmers.
- IPM portfolio economies: Different IPM tactics work together as a portfolio. Farmers want to use a minimum number of different tactics for the maximum benefit. In some instances, it is possible to replace a conventional synthetic chemical pesticide with a biopesticide without disturbing the existing pest management system. However, IPM tactics may be synergistic, such that one tactic in the portfolio results in an improved performance in others, and such interdependencies can make it difficult to introduce new elements.

Chemical Pesticides

Chemical pesticides are used widely to protect against weeds, pests and diseases. These compounds are the mainstay of global crop protection. As one major problem, they increase the likelihood of resistant organisms. Development and implementation of pest resistant management strategies are required to prolong the useful life of pesticides (Royal Society 2009, p. 30).

Potential is seen for a novel class of crop protection chemicals that are fundamentally different from those most widely used at present. The novel compounds would resemble chemicals present in plants that activate or prime natural resistance mechanisms and, because they do not target pests and pathogens directly, they could have environmental advantages over currently used compounds (Royal Society 2009, p. 30).

On the other side, many chemical pesticides will move out off patent. As these chemicals become generic pesticides, the original manufacturers lose their monopolies on them. Rising sales of generic pesticides, especially in countries in Africa and Latin America but also in some Asian countries, is often facilitated by weak regulatory control. Around 30% of pesticides marketed in developing countries do not meet internationally accepted quality standards. Possible causes of low quality of pesticides can include both poor production and formulation and the inadequate selection of chemicals. They are posing a serious threat to human health and the environment (FAO 2009). Additionally, cheap generic pesticide can thwart integrated pest management programmes.

In Europe, the new EU pesticide regulation (Box 3) includes a shift of authorization from risk-based assessment of substances to hazard-based criteria. This approach entails the ban of plant protection products containing substances that are genotoxic, carcinogenic or toxic for reproduction, and that have neurotoxic, immunotoxic and endocrine-disrupting properties, the so called "cut-off" criteria. This will probably lead to the ban of large classes of pesticides. This regulation could stimulate the agrochemical industry to diversify its search for new pesticides and to look for compounds with little health and environmental concerns (Labussière et al. 2010).

4.2.6. Conclusion

A broad spectrum of existing and emerging knowledge, technologies and practices has the potential to contribute to sustainable intensification. But implementation of a single technology or practice promise only restricted advances. This is so because single technologies/practices have to be fitted in the more or less complex overall farming system and the specific crop production system, and increased productivity (yields, efficiency) is the result of system interactions. Therewith, only with system-based approaches real progress in sustainable intensification can be expected.

Same of the discussed technologies/practices have close links to the crop production systems (Chapter 4.1.). For example, diversified crop rotations are a key element of conservation agriculture, organic farming and agroforestry, and are important in integrated crop-livestock systems. No-tillage is a constitutive element of conservation agriculture, and agro-ecological approaches in pest management are essential for organic farming. The relevance of a number of technologies and practices for different crop production systems indicate that chances for combinations of crop production systems exist. Such combinations are already partly practiced. Therewith, crop production systems should not be regarded as closed systems.

The discussed technologies and practices are of different complexity. For example, integrated nutrition management and integrated pest management compromise in itself a whole set of practices to consider. Therewith, they are an indicator for the higher complexity of modern crop management which is at the same time a challenge for farmers.

The technologies and practices for sustainable intensification are described and assessed according to their main objective: Overall crop production management, soil management, water management, nutrition management, and pests, diseases and weed control management. Many options do not address one single objective, but have important implications also on other key features of crop management. The arrangement of the crop rotation is a prominent example, influencing soil properties, water and nutrient demand, and affecting pest, disease and weed pressure. Therewith, the overall arrangement of crop production for a number of years (such as rotation, green manure and intercropping) plays a key role for improved crop production management. Economic incentives for specialisation and simplification in crop production are a major constraint for more diversified crop rotations.

Another key issue is the improvement of soil fertility. A number of options is available. This is of high relevance of stabilizing achieved yield levels in favourable areas, realising more of the exiting yield potentials in areas with higher yield gaps, and increasing the resilience of farming systems. Broader implementation and better adaptation of such existing technologies and practices could facilitate improved site specific yield potentials. More complex agro-ecological approaches need time to fully display their beneficial impacts.

Additionally, a set of options for improved input efficiency is available. They include improvements in sowing, soil preparation, irrigation, fertilization and pesticide application. Variable rate technologies are an important approach. Beside increased input efficiency, they can also contribute to higher yields in many cases. Once again, attunement of actions in the different steps of crop production is important.

Simplified schemes of differentiation in high-tech and low-tech approaches are not appropriate. Techniques such as variable rate technologies with sensors and modern biopesticides classify as high-tech approaches, needing intensive research and development. But so called low-tech approaches entail extensive knowledge and skills. They demand also research activities at both research and farm level to support local adaptations and adoption.

Not all possibilities are suitable for a specific farming system. Generally, technologies and practices have to be customised to the on-site farming conditions, the natural and socio-economic circumstances of a farm. Not all approaches can be applied on a specific farm at the same time because capacities and time are major restricting factor in farm management.

5. PLANT BREEDING: INCREASING THE YIELD POTENTIAL

5.1. Introduction: History of scientific based plant breeding

First breeding attempts started about 10,000 years ago with the domestication of plants: those plants were selected that showed particular favourable traits, such as pleasant taste or larger size of fruits (Cox 2009, p. 3; Acquaah 2007, p. 3; Hallauer et al. 2011). At that point of time, inheritance on the genetic level was enigmatic and selection was solely done by phenotype, thus the appearance of an individual plant (Cox 2009, p. 3). Davies (2003) attributes the first implementation of controlled crosses to the German botanist Joseph Kohlreuter who analysed the ornamental plant *Dianthus herbatus* in his studies in the late 18th Century. The basic foundation for scientific based plant breeding was the description of the legality of heredity by the Austrian monk Gregor Mendel in the middle of the 19th Century. His findings were the foundation for methodical plant breeding which started thenceforward. Since then different classical breeding methods have been developed which mainly base on his three laws. The knowledge about the biological background of inheritance has greatly increased and biotechnological tools in plant breeding have consistently been developed and improved. These great achievements on the scientific level in plant breeding have led to impressive yield increases (see chapter 2.2). Besides the improvement of agricultural technologies, plant breeding has contributed to plant improvement to a high extend. The different estimations of the contribution of plant breeding to yield increase range from 25-50% (Friedt, Ordon 1998; Ordon 2011).

While conventional breeding work in the past, where plants could only be evaluated by their phenotype, took mainly place in the field and transferring a favorable trait to a new variety took at least 10-15 years (Jauhar 2006), plant breeders nowadays have numerous modern tools and technologies to accelerate the process of transferring specific genes of interest and/or identifying potential candidates on the genetic level to create new varieties, thereby using modern laboratory methods, statistical models and sophisticated bioinformatics. The invention of modern biotechnology has speeded up the regular breeding process immensely (Hock et al. 2003).

5.2. Overview breeding technologies and goals

5.2.1. Definitions of plant breeding

There is no general definition of the term “plant breeding”. Different approaches describe the main aims of plant breeding as a science and practical handcraft as well. Highlighted aspects are:

> permanent and heritable changes of plants (Acquaah 2007, p. 3);
> application of genetic principals (Friedt, Ordon 1998);
> creation of varieties which deliver high and stable yields under changing environmental conditions (Friedt, Ordon 1998);
> development of individuals or cultivars more suited to the needs of humans (Schlegel 2010, p. 274);
> not just an objective truth but represents also a “social construction” and thereby also has to be seen from a social point of view regarding social acceptation and demands (Cleveland 2001).

5.2.2. General breeding goals

Plant breeders are confronted with a multiplicity of sophisticated breeding goals while creating new varieties. For example, breeding goals for a new wheat variety can be grain development and size, cold hardiness, stableness, protein content, baking quality and resistances against diverse pathogens, such as fungi or insects. Plant breeding nowadays does not only try to increase the yield of a variety, but especially to provide a high and stable yield in combination with a high quality of the product. As there is a drastic reduction of the potential yield of many crop plants due to pests and pathogens, plant breeding for resistance is of utmost importance too. Summarized there are three major breeding goals in plant breeding (Becker 1993):

- Yield potential
- Yield safeguarding
- Quality

5.2.3. Basis for inheritance

All plant traits are encoded by genes. Genes are particular DNA-sequences composed of the four DNA basic modules adenine, thymine, guanine and cytosine. The special sequence of these components encodes the expression of the trait. The characteristic of a particular trait is generally not only affected by its encoding gene or genes, but also by environmental influences.

In this context one has to differentiate between monogenic and polygenic inherited traits. Classical monogenic inherited traits such as the color of the flower or resistance towards a particular pathogen are encoded by one single gene that mainly affects the occurrence of the trait. These monogenic inherited traits are normally rarely affected by environmental influences and are thereby easy to select.

But most of the agronomic favorable traits, such as yield or abiotic resistances are not only encoded by a single gene (inherited monogenic), but depend on the influences of several different genes that strongly interact with themselves as well as with the environment. This sort of inheritance is called "polygenic" and has challenged the plant breeders since the beginning of methodical scientific based plant breeding. Therewith, typical polygenic traits like yield can extremely vary under changing environmental conditions, such as temperature. The chief attraction for the breeder is to create a variety that shows a stable performance in difference environments, delivering high and stable products of high quality.

5.2.4. Major steps in plant breeding

In general, every plant breeding approach follows three major steps (Wyss et al. 2001; FAO 2011c, p. 6 and 7):

- Creation of a new initial genetic variation;
- Selection of suitable crossing parents for creating new varieties;
- Testing, maintenance and reproduction of a variety.

The first major step in breeding is to create a broad genetic variation where genes are recombined and are present in different compositions in individual plants. This represents the basis from which the selection of potential candidates for new varieties takes place (Friedt, Ordon 1998).

In the second step the breeder then tries to identify individuals that carry the wanted traits or combinations of traits in order to select and re-use them for the next steps in his breeding program. While in the past the breeder could only include phenotypic detectable, easily measurable external and internal traits such as plant habitus, yield or measurable resistance against different pathogens or diseases in his validation for selection, he has now the opportunity to select plants based on genetic information and data. The breakthrough in this context was the advent of molecular markers in the 1970s and the development of marker assisted selection (MAS) (Brumlop, Finckh 2011).

The third main step in breeding new varieties mainly deals with the testing, maintenance and reproduction of a new variety. Before a new cultivar can be launched, it first has to be tested in perennial and multi-spatial trials. Thereby several requirements have to be fulfilled, such as the innovation and newness of a new variety, its purity and homogeneity and its reproducibility. These factors are tested by independent institutions which can finally permit or decline the market entry of a new variety (Wyss et al. 2001).

5.3. Plant breeding technologies

5.3.1. Overall breeding strategies and conventional breeding

Different plant species have different types of propagation so that different breeding strategies have to be applied from which result four different major types of varieties, shown in table 24 (Borlaug 1983).

Table 24: Propagation systems, Types of reproduction and types of varieties

Natural type of propagation		Process of reproduction	Type of variety
asexual propagation	→	vegetative propagation	clonal variety
autogamy	→ ↘	self-fertilization	line variety
	↘ ↗	controlled crossing of heritage components	hybrid variety
allogamy	↗ →	open pollination	open-pollinated variety

Source: Becker (1993), p. 191

Breeding for clonal varieties

Plant species such as strawberries, sugarcane or potatoes are classical representatives for vegetative propagation which means that besides sexual reproduction they are able to reproduce themselves asexually. After sexual crossing of two suitable parental lines to create a genetic variation, candidates are selected and propagated vegetatively based on plant parts. The products are clones that are genetically equal with their ancestor.

The advantages of vegetative propagation are that plant material obtained by this technique is highly uniform and pure. Predominantly ornamental and bulbous plants as well as fruit trees are reproduced by vegetative propagation (Friedt, Ordon 1998; Bette, Stephan 2009; Bisognin 2011).

However conventional vegetative propagation also has its disadvantages. On the one hand, the technique is connected with relatively high costs because the plants are not propagated by seeds but by scions; this also limits the capacity of the procedure. Normally, the first generation after crossing of two plant genotypes does not directly have the favourable characteristics. This requires an upstream multilevel breeding procedure for several generations also for vegetatively propagated crops which is again connected to high costs. On the other hand, conventional clonal propagation of plant material is prone to spreading of pathogens present in the ancestor plants as well as to spreading of unwanted mutations. For example it might be the case that a random mutation in the genome leads to a change in the flower colour. Legally, the propagated mutated variety represents a so-called “essential derived variety” which means that its genome is basically identical with the already existing variety and thereby falls under the legislation of the plant variety protection of the ancestor variety (Bette, Stephan 2009).

With the invention of tissue culture-based methods rapid in vitro propagation techniques, such as micropropagation, become more and more important. However, this modern technology, although generally available and very promising, is still restricted to many breeding programs worldwide. This is mainly caused by relatively high costs of the method. Because most of the breeding programs of horticultural crops in the world are conducted and funded in the private sector, mostly by huge multinational seed companies, farmers are depended on cultivars from big companies (Silva Dias 2010).

To attend the demand for commercial production importation is mandatory. For example seed potatoes are imported from Netherlands, Canada, Chile, France and Scotland, strawberry plantlets are imported from Argentine and Chile. To reduce production costs and to make rapid propagation techniques available to small holders, public investments should be done. However, there are crops like sweet potato which show high rates of mutations in tissue culture applications. Therefore, vegetative propagation in this case is still mainly done by stem cuttings (Bisognin 2011).

Breeding self-pollinated species

Self-pollinated plant species are bred by pure-line breeding methods using the natural self-fertilization mechanism of the plants. After crossing of two parental lines the seeds are harvested and sown in the next generation. The generated plants are then propagated by self-fertilization for several generations, thereby selecting those individuals showing favourable characteristics of a trait. This repeated process of self-pollination results in varieties that are highly homogzygous. Typical plant varieties produced by self-pollination are wheat, rice or barley. The classical and conventional methods of breeding self-pollinated species remain essential for crop improvement as other techniques are not available for some self-pollinated species. This is for example the case for winter wheat which is still mainly bred using conventional techniques because of its incompatibility for hybrid breeding techniques so far (Dedieu 2010). However, conventional pure-line breeding is nowadays often supported by modern techniques, such as marker-assisted selection.

Breeding cross-pollinated species

Open-pollinated varieties represent heterozygous, heterogeneous populations that result from cross-breeding methods for cross-pollinated and facultative allogamic species (Friedt, Ordon 1998, p. 29), such as cotton, rapeseed, rye, sunflower and fodder beet. After an initial crossing of two parental lines the plants in the next generations are propagated by open pollination which means, that all genotypes in the population are fading together. One of the most important and best established methods for breeding cross-pollinated and facultative allogamic species is the hybrid breeding method. Today conventional cross-pollination breeding techniques are predominantly used to create new initial variation for further hybrid breeding steps as the method is relatively cheap and requires no costly laboratory techniques (Arncken, Dierauer 2005, p 7).

Landraces

Landraces, also known as “local or traditional varieties” (Betrán et al. 2009, p. 37) represent “a set of populations or clones of a crop species produced and maintained by farmers” (Schlegel 2010, p. 214). They are highly heterozygous and show relatively low yields in comparison to high performance varieties under high-input agriculture conditions. But landraces are well adapted to their domestication regions, often with low external input farming, and thereby deliver high yield stability (Acquaah 2007, p. 88). Providing a high genetic diversity, landraces represent suitable initial breeding material for professional breeding programs (Schlegel 2010, p. 214; Acquaah, p. 88; Weltzien, Christinck 2009, p. 89).

Especially cereal landraces played a fundamental role for food production worldwide in the past. This has changed with the invention of scientific based plant breeding in the late 19th century and the development of modern varieties, bred for high-input agriculture systems (Newton et al. 2010). In the second half of the last century their use has declined dramatically (Pinheiro de Carvalho et al. 2013).

The global use of landraces for food production varies remarkably. While landraces play an important role for farming and food security in marginal regions, especially in developing countries, developed countries with high-input agricultural systems are dominated by modern high-performance varieties. In Africa for example, about 80 percent of the cultivated seed are local varieties or landraces from the informal sector. The remaining 20 percent formal seed are exclusively composed of hybrid maize and ornamental seed (Wekundah 2012).

In Europe, landraces mostly do not account for food production to a big extent and only play a role in small-scale farming systems in poorer marginal regions. However, they still contribute to food security in some regions with heterogeneous climate conditions, like in Bulgaria (Krasteva et al. 2009, p. 65). There is no available exact information about crop production with usage of landraces. However, it can be assumed that landraces in those regions of the EU which are dominated by small-scale or and subsistence or semi-subsistence farming systems. Countries with over 10 percent "Utilised Agricultural Area" (UAA) covered by small-scale farmers are Romania, Latvia, Lithuania, Austria, Malta, United Kingdom and Poland and these are European regions in which landraces most likely play a role for food production.

Besides the importance for food production in some regions of the world, landraces are also very important for genetic diversity and plant breeding purposes. Therefore, the concept of "genebanks" has been invented to store and maintain plant varieties, landraces and their wild relatives to keep up genetic diversity (Newton et al. 2010). Hence, landraces represent both the moth important source of variability for plant breeders and a basis for profitable markets for local people (Veteläinen et al. 2009, p. 306).

In 2012 there were a total of 1750 gene banks worldwide maintaining 7,420,236 germplasm collections including landraces. Europe has the largest number of gene banks (481) maintaining plant material of different crop plants and their relatives (Pinheiro de Carvalho et al. 2013). There is a general opinion that in the course of the evolution of plant breeding in the last century plant genetic diversity is threatened by the loss of landraces in agriculture and the domination of genetically uniform modern varieties in many agricultural production systems. Therefore, the Directive 2008/62/EG was approved which aims to preserve agrobiodiversity. However, there are critics that see problems with the "loose" wording of the directive which results in different national interpretations. For this reason there are concerns whether this directive will be of great help in preserving all the diversity maintained up to now in Europe (Negri et al. 2009, p. 13 and 14). It is most likely that the role of landraces will remain very important for plant breeding.

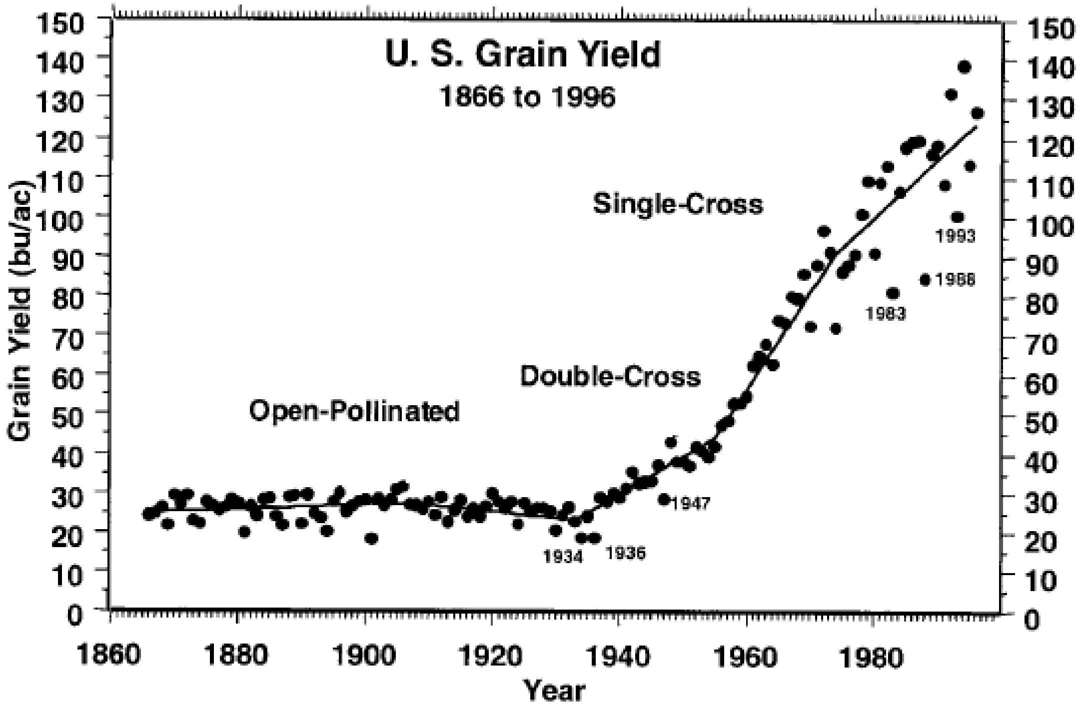
Due to their importance for maintenance of genetic diversity, breeding purposes and food security it is most likely that landraces will keep a crucial role for the future. However, the legal frame limits a wider distribution and usage of landraces as they do not fulfil the requirements for variety registration due to their heterogeneity. By inventing special regulations for landrace authorisation this problem could be solved. An example is given by Switzerland where landraces can be authorised as "niche varieties" since 2010 (Messmer et al. 2012, p. 8).

Hybrid breeding

Hybrid varieties generally represent the first filial generation (F1-generation) of a crossing between two homozygous, genetically diverse parental inbred-lines. The F1-population shows a distinct superior performance in comparison to its parental lines which is called "heterosis effect". The heterosis effect gets lost in the next generation (F2) which means, that farmers cannot produce own seeds out of hybrid varieties. They are forced to obtain hybrid seeds from breeders every year which some breeders consider as an "inherited intellectual property (IP) protection" (Wiel et al. 2010).

Remarkable success in yield increase has been achieved by the invention of the hybrid breeding methodology in the early 20th century. Representing the most popular and important breeding methodology for open-pollinated species, hybrids often outyield traditional open-pollinated vegetable varieties by 50-100 % (ISAAA 2004). The most astonishing example for the impact of hybrid breeding on crop improvement is given by the development of maize. Since the market entry of the first maize hybrid varieties in 1930 maize yields have quintupled until the year 2000 (Crosbie et al. 2006) which is shown in figure 14.

Figure 14: Maize grain yields in the USA from 1866 – 1996



Note: bu/ac = bushels per acre; Double-Cross and Single-Cross are hybrid-breeding methods
Source: Crosbie et al. (2006)

The importance of hybrids is also underlined by the fact that today nearly all corn and many of the rice varieties grown in china hybrids (Longin et al. 2012; ISAAA 2004). More than 664 high yielding and 83 high quality maize hybrids have been recognized by the State regulations of the USA since 1964 (Konstantinov et al. 2012). Similar results were achieved for other crop species such as soybean, sunflower or tomato (Konstantinov et al. 2012).

The hybrid breeding technology is not automatically transferable to any crop plants as it has originally been invented for breeding open-pollinated, allogamous crop species. One example is given by wheat, which is autogamous and represents the second most important cereal worldwide (Dedieu 2010). For at least three decades researchers have tried to establish the hybrid breeding method for wheat production, but only with moderate success. Especially the complexity of the wheat genome limits the success of the technique, making classical pure-line breeding approaches more feasible for wheat production until now. However, after years of intense research, wheat hybrids are at least getting more important, although they do not play a dominant role on the seed market by now. This is underlined by the fact that only 1% of the total wheat area is planted with hybrids. More than half of the world's wheat hybrids are grown in Western Europe on 200.000 ha, mainly in France (160.000 ha) and Germany (25.000 ha) (Longin et al 2012). Nevertheless it is assumed that wheat hybrids offer great potential for yield increase in the future. For example, Syngenta, one of the leading seed producing companies worldwide, points out in an interview that they are intensely working on wheat hybrid breeding and expect to have countable successes given by wheat hybrid varieties even in this decade (Bechman 2012). One example for a high yielding well established wheat hybrid is given by a French variety called "Hystar" which is well established in France and delivers about 1 ton increased yield per hectare, compared to other high yielding pure-line wheat varieties (Dedieu 2010).

Maize hybrids planted in the USA exhibit yield averages ranging from 9-40 % compared to the best open-pollinated cultivars. The invention and further usage of maize hybrids since 1930 is assumed to account for 60-70 % of the yield gain in maize (Kutka 2011; Acquaah 2006, p. 339). Crosbie et al. (2006,

p. 8) extend this range to 56-94 %. Stamp and Visser (2012) state that only hybrid seeds provide a solid return on investment and that for this reason breeders predominantly focus on plant species on which hybrid breeding methods can be applied. From an economical point of view, breeding self-pollinating crops with pure-line breeding methods, such as wheat are less interesting because they can be propagated by farmers themselves.

There are many popular vegetables and ornamental hybrid varieties because they deliver distinct improvements regarding yield, performance and quality in comparison to traditionally bred varieties (ISAAA 2004).

There is still potential to further exploit the heterosis effect and thereby increase the breeding success of the hybrid breeding method (Aguirre et al 2012). More efforts have to be made in identifying the best combinations of parental lines for creation of high-performing hybrids. This is in progress by using modern breeding approaches such as molecular markers or novel genotyping approaches using DNA sequencing methods in hybrid breeding programs. Another elementary task for hybrid breeding research is to reveal the molecular basis of the heterosis effect. This is in process and could extremely contribute to improving the hybrid breeding method in the near future (Ordon 2011).

5.3.2. Mutation breeding

Mutation breeding approaches follow the principle to artificially induce mutations throughout the plant genome using chemical or physical agents in order to create new genetic variation for traits of interest. The induced mutations are randomly and changes in gene functions are thereby undirected (Pathirana 2011). Table 25 compares mutant with transgenic plants.

Table 25: Comparison of mutant and transgenic plants

Affecting stage	Mutant plants	Transgenic plants
Principle of the method	Mutagenesis can only modify existing genes of an organism; mutagen treatment fragments DNA sequence first, followed by DNA repair mechanism, with the result of mutations (changes) in the sequence composition.	Genetic engineering can directly add new gene/genes in the plant genome; transferred genes can be from any source including animals, insects, plants, and bacteria; transgene or cisgene integrates into plant genom randomly.
Type of genetic variation	Mutation is a random event, covering the whole genome and all genes respectively.	Specific genes are isolated, cloned and incorporated in a directed manner by using tools of molecular biology.
Number of plants required	Requires large populations for screening the best desired mutants.	Genetic modification can be applied on single plants which are then propagated after successful genetic modification.
Affected region in DNA sequence	Mutants can carry changes in non-target genes which can lead to unexpected changes in gene functions.	Functions of genes and proteins are well understood for many crop plants; specific known genes are incorporated in plant genomes in order to reach an expression of the favourable trait.

Source: Changed from Jain (2010)

Since the discovery of the technique in the early 20th century it took over 40 years to establish the method in a way to reach profitable successes (Lönnig 2005). Henceforward, especially since the invention of high-throughput mutation screening methods, mutation breeding has become an important tool for plant breeding and crop improvement. Today the technique is employed all over the world. There are more than 2,300 mutagenesis-derived varieties on the market; almost half of them have been released during the last two decades and are registered in the IAEA ("International Atomic Energy Agency) database (ISAAA 2010, Jain 2005). The main projects in South East Asia focus on genetic improvement of ornamental plants, cereals and fruits (Jain 2005). Projects in Africa concentrate on cassava, date palm, salinity and drought, whereas projects in the Middle East mainly deal with tolerances to salinity and drought. Nuclear technology furthermore offers great potential for somatic cell hybridization. This means, that nuclear irrigation could effectively be used as an induction agent for protoplast fusion to create intergenic hybrids out of genotypes that are naturally not combinable, making the protoplast fusion method more efficient.

Jain (2010) rates mutation breeding as highly necessary to enhance genetic variability since spontaneous mutations occur very infrequently. Furthermore the method is assessed to play an important role in breeding programs in the future, especially in combination with tissue culture-based methods (Jain 2010). On the one hand, mutagenesis can lead to multiple trait mutants which is an advantage compared to genetic modification, where only single traits are introduced in a plant. Additionally, there is a lack of acceptance of genetically modified food which gives mutation breeding a superior role for practical application (Jain 2010). Novel mutagenesis approaches, such as TILLING ("Targeting Induced Local Lesions IN Genomes") are very powerful tools for rapidly screening big populations for interesting and promising mutations and localize them in the genome. TILLING is nowadays incorporated in different professional breeding programs making the mutagenesis method more efficient for crop improvement (Pathirana 2011).

5.3.3. Tissue culture techniques

All tissue culture-based methods follow the principle to cultivate single plant cells, tissues or organs in special culture medium *in vitro* in order to generate plant organs or whole plants (ISAAA 2010). Generally, tissue culture methods can be applied for nearly all crop plants and are also applicable for many developing countries for crop improvement. Since the invention of the principle in the 1940s, different tissue culture approaches have been developed (Suslow et al. 2002).

Embryo rescue method

Plant species that are not related or genetically widely different cannot or only rarely be crossed by conventional methodologies due to biological crossing barriers that inhibit the correct development of either seeds or the whole plant respectively after crossing (Schlegel 2010, p. 136). Doing wide crosses between naturally not combinable plant species has become an important tool in plant breeding to increase the genetic variation for a particular trait (Friedt, Ordon 1998). The embryo rescue method was invented to overcome the post-fertilisation crossing barrier. The principle of the method is to isolate the growing embryo from the seed after a wide crossing, cultivate it on special culture medium that contains plant growing hormones and nutrients and finally generate a whole plant hybrid *in vitro* out of the isolated embryo (Suslow et al. 2002).

The method is well established and has been widely used to produce inter- or intraspecific hybrids to enhance genetic variation and combine agronomical important traits (Friedt, Ordon 1998; Reed 2005). There are many examples for the successful application of the embryo rescue method. For example, fungal resistances of topinambur could successfully be transferred into sunflower. Furthermore, nematode resistances from oil radish have been transferred to oilseed rape and the cereal crop triticale was also created by combining wheat and rye using the embryo rescue method (Friedt, Ordon 1998). There are also reports about the successful employment of the technique for rice varieties which are cultivated in West Africa. "NERICA" (New Rice for Africa) origins from a cross between an African, local adapted variety and an Asian high yielding variety. The new plants showed high yields and were well adapted to the growing region in Africa. The "International Rice Research Institute" (IRRI) uses the method for transferring bacterial blight resistance genes from wild rice to existing rice varieties (ISAAA 2010). Well established wide cross-enabling techniques like the embryo rescue method will keep their importance for maintaining and increasing genetic variation and for crop improvement in the future.

Protoplast fusion

Protoplast fusion represents another tissue culture based method to overcome natural crossing barriers between not or rarely combinable plant genotypes that inhibit a sexual crossing initially (Haussmann, Parzies 2009, p. 109). Protoplasts are cells that have no cell wall due to enzymatic treatment. They can generally be taken from anywhere of the plant and be chemically stimulated to fuse in special medium. By fusion of two protoplasts the genetic material of the two donor-genotypes is combined. The fused protoplasts can afterwards be generated to whole plants in culture medium (Schlegel 2010, p. 289).

Although this method theoretically provides the possibility to do crosses between any plant species and genius, the literature describes it as relatively complicated and difficult to apply (Dagla 2012; Friedt, Ordon 1998). The main limitations of protoplast fusion include the recalcitrance of some protoplasts to express their totipotency (Davey et al. 2005) and an insufficient fertility of the produced progeny (Wang et al. 2013). Therefore the technique has predominantly been used in plant breeding research in the past, rather than in commercial breeding programmes; but with remarkable success. One example is the successful transfer and establishment of the cytoplasmatic male sterility (CMS) gene from radish into rapeseed. This was an important foundation for hybrid breeding in rapeseed (Ordon, Friedt 1998).

Today, the protoplast fusion technique has become more and more important, having great potential for future commercial use. There are various crop plants that could successfully be improved using the technique, such as wheat, rapeseed, citrus, potato or cotton (Wang et al. 2013). The following table 26 shows some recent examples of the transfer of useful agronomic traits by protoplast fusion. The different applications for various important crop plants underline the growing importance of the protoplast fusion technique for crop improvement.

Table 26: Recent examples of the transfer of useful agronomic traits by protoplast fusion

Combined plants	Useful traits transferred
Brassica ("cruciferous vegetables, “cabbages” or mustards")	
B. napus (+) B. rapa	Increased biomass and yield*
B. napus (+) Crambe abyssinica	Increased erucic acid content in seeds*
B. napus (+) Orychophragmus violaceus	Improved fatty acid composition in seeds*
B. napus (+) Sinapsis arvensis	Enhanced resistance to Blackleg (Leptosphaeria maculans)*
B. oleracea (+) Moicandia arvensis	Introduction of the C3-C4 intermediate trait [-]
Raphanus sativus (+) Diplotaxis tenuifolia	Introduction of the C3-C4 intermediate trait [-]
Citrus (citrus plants of different kinds)	
C. amblycarpa (+) Citroncirus webberri C35	Improved rootstock for Mexican lime [-]
C. limonia (+) C. sunki cv Tanaka	Tolerance to citrus blight, tristeza virus and Phytophtora [-]
C. reticulata cv Blanco (+) C. paradisi	Production of mixoploid plants tolerant to citrus exocortis virus (CEV) [-]
C. reticulata cv Blanca (+) Poncirus trifoliata	Tolerance to citrus blight, tristeza virus and Phytophtora [-]
C. reticulata cv Blanco (+) C. volkameriana	Resistance to CEV [-]
C. sinensis cv. Rohde Red (+) C. volkameriana	Tolerance to citrus blight, tristeza virus and Phytophtora [-]
C. sinensis cv. Ruby Blood (+) C. volkameriana	Tolerance to citrus blight, tristeza virus and Phytophtora [-]
C. sinensis (+) Fortunella crassifolia	Increased plant vigor*
C. sinensis (+) F. obovata	Tolerance to citrus blight, tristeza virus and Phytophtora [-]
C. sinensis (+) Clausena lansium	Production of triploid plants*
C. unshiu cv. Guoqing No. 1 (+) C. grandis cv. Buntan Pink	Generation of seedles cybrids [-]
C. unshiu cv. Guoqing No. 1 (+) C. reticulata cv. Blanco	Generation of seedles cybrids [-]
C. unshiu cv. Guoqing No. 1 (+) C. reticulata x C. sinensis	Generation of seedles cybrids [-]
Solanum ("nightshades", "horsenettles")	
S. melongena (+) S. aethiopicum	Resistance to bacterial wilt (Ralstonia solanacearum)*
S. melongena (+) S. sisymbrifolium	Resistance to bacterial and fungal wilts*

S. tuberosum (+) S. etuberosum	Resistance to potato virus Y*
S. tuberosum (+) S. nigrum	Resistance to potato blight (Phytophtora infestans) [-]
S. tuberosum (+) S. stenotomum	Resistance to bacterial wilt (R. solanacearum)*
S. tuberosum (+) S. chacoense	Resistance to bacterial wilt (R. solanacearum)*
Triticum (Wheat)	
T. aestivum (+) A. elongatum	Resistance to drought and salinity [-]
T. aestivum (+) A. sativa	Good adaptability, high protein and fat content in seed [-]
T. aestivum (+) B. inermis	Tolerance to cold, drought and diseases [-]
T. aestivum (+) H. villosa	Resistance to diseases, high protein content [-]
T. aestivum (+) L. chinensis	Resistance to cold, drought, salinity and diseases [-]
T. aestivum (+) Psathyrostachys juncea	Tolerance to drought and salinity [-]
T. aestivum (+) S. italica	High nutritional value and drought resistance [-]
Gossypium ("cotton plants")	
G. hirsutum (+) G. davidsonii	Disease resistance [-]
G. hirsutum (+) G. klotzschianum	Disease resistance [-]
G. hirsutum (+) G. stockii	Disease resistance [-]

Notes: * Trait transfer is confirmed
[-] Trait transfer unconfirmed
Source: Davey et al. (2005), Wang et al. (2013)

In the last decade there has been a significant resurgence of interest in protoplast fusion technology mainly focussing on combining genotypes that cannot be crossed by conventional methods (Davey et al. 2005).

Haploids and double haploids in plant breeding

Generally, every fertile plant carries a doubled set of chromosomes (2n) in its cells containing one set of its ancestor respectively. In the process of gamete production (meiosis; producing pollen or ovules) the diploid set is recombined and reduced to a haploid set (1n) to maintain genetic variation and a constant number of chromosome sets over generations of crossing events.

Especially for breeding pure-line and hybrid varieties, it is important to produce either highly homozygous varieties for commercialization or highly homozygous parental lines for hybrid production with a maximum heterosis effect (Crosbie et al. 2006). This procedure may take up to ten years to achieve using conventional breeding methods (Crosbie et al. 2006). In this context the double haploid technique has been invented. The principle of the method is to isolate haploid gamete cells (1n), cultivate them on culture medium and generate plantlets out of them (Germanà 2011; Seguí-Simarro, Nuez 2008a). Because the plants generated from the gamete cells only carry a haploid set of chromosomes they are sterile. For this reason the plantlets are treated with the natural toxic colchicine which is derived from plants of the genus *Colchicum.* Thereby, the sterility can be reversed as colchicine treatment of plants leads to chromosome doubling and thereby restores diploidy (2n) and fertility (Forster et al. 2007; Friedt, Ordon

1998). Diploid plants produced by this method are called "double haploid" (DH) The invention of the DH method has rapidly shortened the procedure of creating highly homozygous genotypes.

Since the discovery of haploid plants in 1920 and especially after the discovery of "androgenesis" (also called "pollen embryogenesis") in 1964, doubled haploidy has become a widely used tool in plant breeding. The DH technology is still the method of choice for creation of completely homozygous genotypes in the shortest possible time (Murovec, Bohanec 2012).

Brennan and Martin (2007) point out that the application of the DH technology in a breeding program can reduce the release time of a new variety and thereby increase the economic value by 20-30 %. The DH technology has been successfully applied in breeding programs for diverse crop species such as asparagus, barley, eggplant, melon, pepper, rapeseed, rice, tobacco, triticale, wheat and maize. By now, more than 290 varieties produced by DH technology have been released. Furthermore, haploids and doubled haploids have widely been used in genetic studies, such as gene mapping, marker analysis and QTL mapping (Murovec, Bohanec 2012).

The usage of doubled-haploidy for crop improvement also represents a feasible tool for developing countries. In Asia and Africa, the DH technology has been used to produce promising new varieties derived from crossings between different Asian and African rice species to combine the most favourable traits. Those approaches were conducted with high levels of farmer participation; new rice varieties have been grown by over 20,000 upland farmers in Guinea which delivered more than doubling yields (Toenniessen 2003).

Murovec and Bohanec (2012) clearly point out that "double haploidy is and will continue to be a very efficient tool for the production of completely homozygous lines from heterozygous donor plants in a single step". The combination of haploid-/doubled haploid techniques and other novel biotechnologies and techniques such as modern mutation breeding, hybrid breeding or genetic transformation have already increased the efficiency of the technique and are assumed to contribute to further progress in crop improvement (Murovec, Bohanec 2012).

Micropropagation

Micropropagation is a tissue culture-based method mainly used for production of asexually propagated plant varieties like strawberries, potatoes or ornamental plants (Suslow et al 2002; Ordon, Friedt 1998). In this method young and actively dividing cells (meristematic cells) are isolated from the ancestor plant and are cultivated on culture medium, thereby generating a great number of genetically identical and disease-free clones of the donor plant. The main problem of traditional clone breeding methodologies in which pathogen contamination of the ancestor plant genotype may be transmitted to the clonal population is overcome by micropropagation because the young meristematic cells from which the clones originate are not contaminated with pathogens. Micropropagated plants show some distinct advantages to conventionally propagated plants like more quickly, vigorously, taller growth and shorter more uniform production cycles at higher yield levels (ISAAA 2010).

At the early stage, micropropagation was a very costly technique, and thereby in most cases not lucrative for practical applications. Since the invention of cost-effective and reliable tissue culture methods, it has become a widely used technique for propagation of diverse crop plants (Jain 2005). Also some developing countries have mastered the technique and it is in current use for crops such as cassava, sweet potato or banana. In African, Asian or Latin American countries, consumables like media, culture containers or electricity make the greatest contribution to production costs. Therefore, there is a need for further development of low-cost methods to make micropropagation more applicable in less industrialized countries (Jain 2005). However, there are documentations about application of plants produced by micropropagation in small-scale farming systems, e. g. for banana production in the East African Highlands. The use of banana seedlings produced by micropropagation could increase the incomes for the farmers and ensure high levels of product quality as micropropagated material is disease-free (Toenniessen 2003).

5.3.4. Marker-assisted breeding

Molecular markers and QTL (Quantitative Trait Loci)

Molecular markers came up in the late 1970s and represent a cornerstone for genetic based plant breeding (Brumlop, Finckh 2011). In traditional breeding approaches plants were selected based on their phenotype and their performance in the testing trials. Depending on how a trait is inherited and how many genes are involved in its expression, the performance of a plant for one trait can strongly differ with changing environmental conditions. Therefore phenotype-based selection is extremely difficult and less reliable for particular traits. The innovation of molecular markers and marker-assisted breeding has tried to overcome this problem, turning phenotype-based selection into a genotype-based method (Ruane, Sonnino 2011, p. 8). The approach to use markers as a basis for selection is called "marker-assisted selection" (MAS). During progress of marker assisted breeding SMART ("selection with markers and advanced reproductive technologies") breeding came up, representing an advancement of the general approach which is described below.

Molecular markers are DNA-regions in genomes whose approximate positions along the chromosomes are defined by previous DNA-analysis and statistical calculations. By incorporating many markers in the analysis, the statistical software calculates a "genetic map" (also called "linkage map") which displays all chromosomes of a genotype including all approximate positions of the markers. DNA analysis is then combined with phenotypic data collection, connecting the marker characteristics to the expression of a trait of interest. Based on the genotypic and phenotypic information for each genotype of a test population, special statistic software can afterwards calculate regions on the chromosomes that are likely to have an effect on the expression of a trait (e. g. yield or drought, cold or salinity resistance). These regions are called QTL ("Quantitative Trait Loci"). A QTL-region can comprise a great number of genes that are interacting amongst each other and with the environment and thereby affecting the trait expression. The markers that are closely flanking a QTL for a trait of interest are assumed to be inherited together with those genes positively affecting the expression of the trait.

Nowadays, there are numbers of different molecular marker systems being developed. The marker systems with the widest use in practical breeding approaches are "random amplified polymorphic DNA" (RAPD), "amplified fragment length polymorphism (AFLP), "short simple repeats" (SSR; also called "microsatellites) and "single nucleotide polymorphism" (SNP) markers (Brumlop, Finckh 2011, p. 55; Maheswaran 2004, Collard, Mackill 2008).

Marker-assisted selection (MAS)

Marker-assisted selection (MAS) describes the approach to select favourable genotypes based on genotypic data. The general procedure of marker development for marker-assisted selection shows figure 15. Theoretically this can be much more reliable than phenotype-based selection, because the genetic conformation of a genotype is not affected by the environment. Furthermore, plants can be selected much earlier in the youth-stages which can speed up the breeding procedure. This is especially an advantage for those traits that are expressed in the late stages of plant development, such as yield or flowering time.

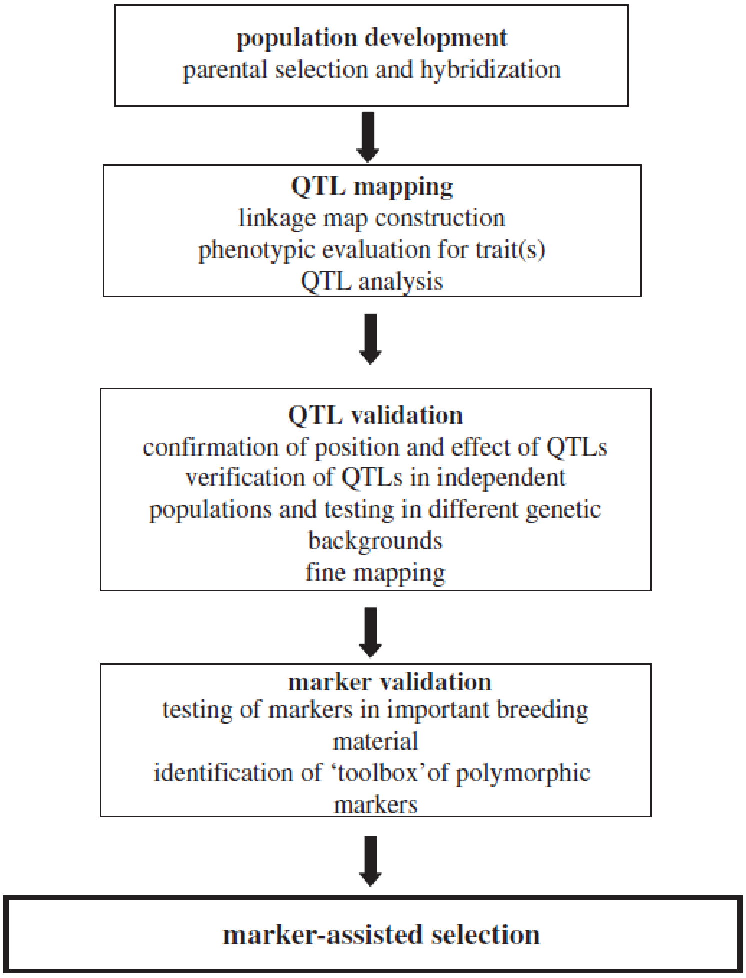
The main applications of MAS in plant breeding are (Collard, Mackill 2008):

- Marker-assisted evaluation of breeding material
- Marker-assisted backcrossing
- Marker-assisted pyramiding
- Early generation marker-assisted selection
- Combined marker-assisted selection

Marker-assisted evaluation of breeding material includes cultivar identification and assessment of purity of a variety, the assessment of genetic diversity and parental selection and the study of heterosis in hybrid breeding programs. In marker-assisted backcrossing approaches the use of molecular markers supports the traditional backcrossing method which has already been invented 100 years ago. In this method, plant breeders cross elite varieties with wild relatives in order to transfer particular trades of interest from a wild species to a high performance variety. After the initial crossing the progeny is backcrossed for several times with the elite variety. Ideally this leads to an improvement of the elite variety for one particular trait. Molecular markers can help to better identify those genotypes carrying the gene of interest. In marker-assisted pyramiding approaches, molecular markers are used to incorporate not only one but several genes in one genotype. Early generation marker-assisted selection means selection and elemination of unwanted genotypes at very early stages of the breeding procedure. This can help breeders to focus on a smaller number of promising high-priority lines. Combined marker-assisted selection combines MAS with phenotypic screening to increase the efficiency and accuracy of selection (Collard, Mackill 2008).

Although MAS theoretically provides a promising tool for crop improvement it always lagged behind expectations (Xu and Crouch 2008). However, molecular markers have the potential to increase the efficiency of selection and are now well integrated into many breeding programs (Brennan, Martin 2007).

Figure 15: Principal marker development for MAS

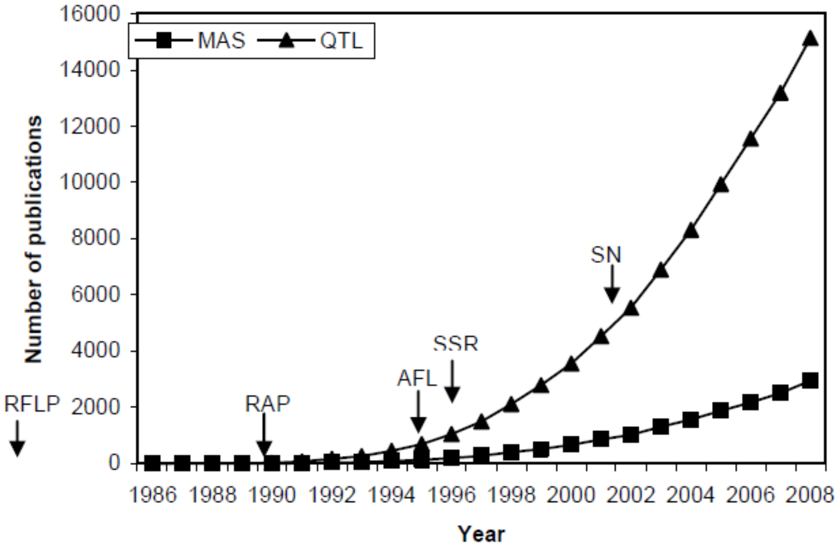


Source: Collard, Mackill (2008)

There are different reasons for the relatively low impact of MAS in practicable plant breeding programs. Collard and Mackill (2008) point out that the MAS technology is all in all in early stages of development. From their point of view there is evidence for a notable increase of studies focusing on MAS in the next 15 years and beyond.

An important limiting factor for a wide distribution and application of MAS technology in practical plant breeding programs is the competition of big seed producing companies amongst each other. Once a MAS approach has successfully been applied in a breeding program it is most likely that a company will not publish MAS results due to economic and competitive reasons. Furthermore, the number of studies validating reported QTL results is much smaller compared to those dealing with novel QTL mapping and identification approaches. This is unfortunate because the validation of QTL mapping results in other test populations offers the most interesting and important information for the applicability of MAS.

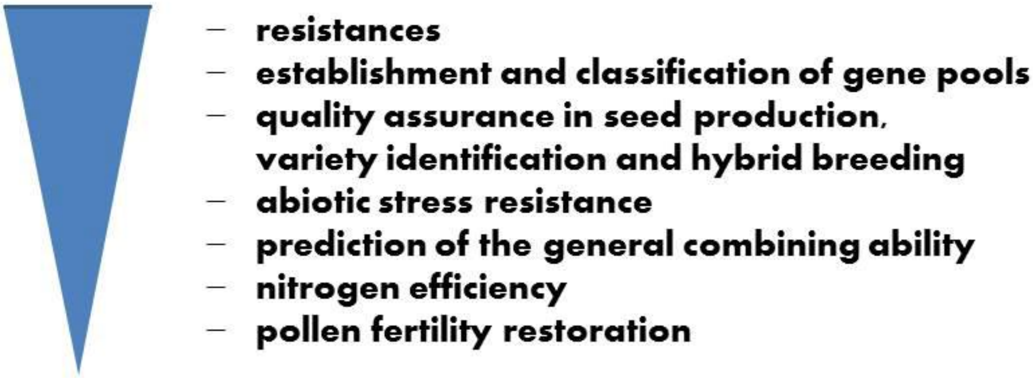
Figure 16: Number of publications for MAS and QTL results in time response



Source: Brumlop, Finckh (2011), p. 44

Figure 16 compares the number of publications for MAS and QTL mapping of the last decades. The most striking factor limiting a wide usage of MAS in plant breeding is that the method is relatively costly (Xu, Crouch 2008; Brumlop, Finckh 2011, p. 45). Brumlop and Finckh (2011, pp. 51-63) could approve this fact by interviewing 14 experts on the field of plant breeding. The results of the interviews expose that a lack of availability of suitable markers for some crop species is another important limiting factor. However, the major opinion of all experts is that marker application in breeding programs will increase in the next 10-15 years. The contribution of MAS to breeding gains strongly depends on the particular crop species. At the moment, molecular markers are predominantly used in hybrid breeding, especially for maize, sugar beets, canola and hybrid rye. Figure 17 shows the main breeding aims for which MAS is applied in breeding companies today.

Figure 17: **Main breeding aims for which MAS is applied in breeding companies today**



- resistances
- establishment and classification of gene pools
- quality assurance in seed production, variety identification and hybrid breeding
- abiotic stress resistance
- prediction of the general combining ability
- nitrogen efficiency
- pollen fertility restoration

Note: Breeding aims sorted downwards by their importance

Source: Modified from Brumlop, Finckh (2011), p. 54

There can be no clear prediction whether MAS or phenotypic selection (PS) will be more useful for crop improvement in the future. However, several studies have tried to compare the gains from both approaches for different traits. For several quantitative traits, MAS had a significant higher selection gain (10.9 %) than PS (6.1 %) (Brumlop, Finckh 2011, p. 20). MAS is seen most appropriate for traits that are difficult and costly to measure. For such traits, the higher selection gain from MAS compensates for the higher costs of the method (Collard, Mackill 2008). In other cases, for example in selecting for resistance to southwestern corn borer in maize, both methods were equal. This was also the case in selecting high protein content or resistance to *Fusarim* head blight in spring wheat (Brumlop, Finck 2011, p. 20).

There are approximately 2,900 patents related to MAS today protecting the intellectual property rights (IPR) of the inventors of the techniques. 890 patents were filed by Pioneer, 498 by Monsanto and 83 by Syngenta. These numbers were taken from a patent database (www.freepatentsonline.com) by Brumlop and Finckh (2011, p. 49) and indicate that the use of MAS is seen as comparative advantage in commercial breeding programs, especially for big seed producing companies.

SMART ("selection with markers and advanced reproductive technologies") breeding

Besides MAS there is the so-called SMART ("selection with markers and advanced reproductive technologies") breeding approach also playing an important role especially in plant breeding research. SMART breeding which was first invented in animal breeding follows the aim to specially analyse the presence or absence of particular gene variants (≙ alleles), making use of modern laboratory molecular-biological techniques. The improvement compared to the classical MAS approach lays in the fact that in SMART breeding genes are analysed. In contrast, MAS detects only the presence or absence of particular markers which are more or less tightly linked to regions or genes in the genome that affect the characteristic of a trait. The SMART breeding approach thereby strongly benefits from the consistent improvement of DNA sequencing technologies as well as the increasing knowledge about gene functions. As more and more crop plants have already been or are in progress to be sequenced and big bioinformatic databases allow an international exchange of knowledge about DNA sequences and gene functions, SMART breeding is assumed to get more importance for crop improvement in the future. However, it is important to notice, that SMART breeding as well as MAS is only a technique for analysing genotypes on the genetic level, but do not affect the sequence composition like in GM approaches. This leads to a much bigger social acceptance than GM techniques (Müller-Röber et al. 2009, pp. 245-250). The "British Beet Research Organisation" (BBRO 2013) estimates that tools of genotypic selection will underpin any approaches to plant breeding in the near future.

The term SMART breeding is often also used to describe biotechnology-assisted modern and innovative plant breeding approaches in general, combining modern laboratory techniques with conventional methods. In other literature it is synonymously used to MAS (Friedt 2007). Therewith, a common definition of SMART breeding does not exist. It must always be seen in the context the term is used.

5.3.5. Breeding with genetic modification

Genetic engineering techniques for crop improvement came up in 1980. They have the aim to directly transfer single genes of interest to plants to create improved varieties passing the laborious procedure of conventional breeding steps (Lusser et al. 2011). Crop plants generated by the use of genetic engineering are called "genetically modified" crops (GM crops). The two most applied techniques for genetic transformation of crop plants are "particle bombardment" and *Agrobacterium*-mediated gene transfer (ISAAA 2010). In particle bombardment, cells are literally been shot with gold or tungsten particles that carry the target DNA or gene respectively. The inserted DNA strand is then integrated in the plant genome by endogenous enzymes (Acquaah 2007, p. 234). In *Agrobacterium*-mediated gene transfer one makes use of the bacterium's natural characteristic to induce its own DNA into plants cells. For usage in genetic transformation, the genetic composition of the bacterium is modified and extended by the target DNA. In a natural process the bacterium then transfers the DNA to the plant cell which is afterwards incorporated in the plant's genome (Einset 1982; Tzifira, Citovsky 2006).

Breeding of transgenic crops

In 2012, the 17th year of commercialization of GM crops, the acreage of GM crops reached 170 million hectares (Table 27), 10 million hectares more from 2011 to 2012. GM crops were grown in 28 countries. From 1996 to 2012, 25 different GM crops and 319 GM events were approved of by competent authorities. Overall, 2,497 regulatory approvals (including approvals for import) have been issued in 59 countries, of which 1,129 are for food use (direct use or processing), 813 are for feed use (direct use or processing) and 555 are for planting or release into the environment. The USA has the highest number of approved events (196), followed by Japan (182), Canada (131) and Mexico (122). For the European Union, 67 approved events have been reported (ISAAA 2012). The five crops with the greatest number of approved events are maize, cotton, potato, canola and soybean. In the USA, 91 GM plants (events) were approved in 2012 for cultivation (Müller-Röber et al. 2013, p. 112).

There are so-called *first and second generation GM crops*. GM crops of the first generation aimed at improved agronomic characteristics such as higher crop yields, resistance to pests or optimising agricultural cultivation. Second-generation GM crops will feature increased nutritional and/or industrial traits, for example rice enriched with iron and vitamins, potatoes with higher starch content and inulin, allergen-free nuts or healthier oils from soybean and rapeseed (Sauter 2005; ISAAA 2011).

Today, only two genetically transferred traits account for 99.9% of the cultivated GM crops, namely Herbicide Resistance (HR) and *Bacillus thuringiensis* (*Bt*) insect resistance, which are either solely present or combined in the particular GM crops (Sauter 2008, p. 7). Only four GM crop species, soybean, maize, cotton and rapeseed, are grown on almost entirely area cultivated with GM crops. Globally, 81% of the cotton, 81% of the soybeans and 35% of the corn planted are GM crops (ISAAA 2012).

In the last years, the cultivation of GM crops with *stacked traits* has increased. Most of these GM varieties are derived by combining previously existing transgenic crops (events) by traditional breeding methods (so called breeding stacks). Stacked trait products with increasing numbers of insect and herbicide tolerance are developed for controlling a broad range of insect pests and weeds. Additionally, technologies for molecular stacking of multiple traits in a single transgene construct (also called transgene arrays) are in development. One of the major uncertainties of molecular stacking concerns the expression of stacked genes over generations, and whether trait efficacy can be maintained in diverse genetic backgrounds under field conditions. In some countries such as the USA and Canada, breeding stacks from previously registered events do not require new safety assessments. In Japan and EU, stacked events are considered as new GM crops and they need regulatory approval, including risk assessment of their safety (Que et al. 2010; Müller-Röber et al. 2013, p. 54-55).

In the EU there are only two GM varieties that are authorized for cultivation. Those are the herbicide-resistant maize variety MON 810 and the stark-enriched potato variety Amflora. While MON 810 is still grown in Europe, predominantly in Spain, the cultivation of Amflora has been stopped in Europe in 2012 due to missing acceptance of consumers and farmers. The EU member states Austria, Hungary, Greece, France, Luxembourg and Germany have banned the cultivation of MON 810 due to ecological risks by now (Biosicherheit 2012). In 2011, there were 19 GMO lines applied for authorization of cultivation in the EU (Umweltbundesamt 2011). In the EU, the majority of GM crop approvals are for imported food and feed (BVL 2013).

Table 27 shows the *global area of GM crops* in 2011, sorted by country in million hectares. The main GM crop producers are the USA, Brazil, Argentina, Canada and India. The GM crop cultivation area in Europe is distinct smaller. 129.071 hectares of *Bt* maize were grown infive EU countries (Spain, Portugal, Czech Republic, Slovakia and Romania) in 2012 (ISAAA 2012). The biggest and most relevant European GM crop producer is Spain with around 116,000 hectares. 90% of the total *Bt* maize in the EU is grown in Spain.

Table 27: The most important countries worldwide growing GM crop

Rank	Country	Area (million hectares)	Percent of total GM acreage (%)
1	USA	69.5	40.6
2	Brazil	36.6	21.5
3	Argentina	23.9	14.1
4	Canada	11.6	7.0
5	India	10.8	6.6
6	China	4.0	2.4
7	Paraguay	3.4	2.0
8	South Africa	2.9	1.7
9	Pakistan	2.8	1.6
10	Uruguay	1.4	0.8
⋮	⋮	⋮	⋮
17	Spain[1]	0.1	0.06
	Total	**170.3**	**100**

Notes: [1] Spain represents the biggest GM crop producer in the European Union
* 17 countries growing 50.000 hectares, or more, of GM crops

Source: James (2012)

Broad attention received *"Golden Rice"* which is GM rice that produce pro-vitamin A (beta carotin) in its seed and could thereby serve to resolve vitamin A deficiency, which blinds and kills thousands of children in developing countries every year (Enserink 2008). In recent years, the IRRI has bred "Golden Rice" traits into important Asian varieties. After more than a decade, it is now advancing towards its admission in the Philippines and Bangladesh and is expected to be first released in the Philippines in 2013/2014 (James 2011). In past, "Golden Rice" was discussed highly controversial if it is an adequate approach to fight malnutrition (Enserink 2008; Sauter 2008, p. 54-58). Programmes to improve the nutritional value of crops such as Harvest-Plus relies almost entirely on conventional breeding. The only charity still investing massively in GM crops with enhanced nutritional value is the Bill and Melinda Gates Foundation, supporting not only "Golden Rice" but also GM cassava, sorghum and banana (Enserink 2008).

The general discussion in Europe about the usage of GM crops for food and feed is highly controversial. On the one hand, the GM technology is seen as one important option to increase agricultural output, to reduce environmental impact, to contribute to rural development and to maintain international competiveness in agricultural innovation (e.g., Bruce 2011; EASAC 2013). The slow and expensive EU GM regulatory framework is seen as a major obstacle (Bradfort et al. 2005; EASAC 2013). On the other hand, non-governmental organization question these claims and argue that hunger is a problem of food distribution, and lack of access to land, water and income, not a problem of insufficient amount of food production.

Different reports of academies of science came to the conclusion that GM crops have no greater adverse impact on health and the environment than any other technology use in plant breeding (Akademien Schweiz 2013, EASAC 2013, Müller-Röber et al. 2013). But especially in regard to environmental impacts, this assessment is dependent from the framing: Are impacts of changes in agronomic practices associated with implementation of GM crops seen as a consequence of GM crops and what reference of sustainable agriculture (e.g., conventional agriculture or organic farming) is employed.

Yield impacts of the GM crops in use are (Qaim 2009; Brookes, Barfoot 2013):

> Herbicide tolerant (HT) crops: The primary impact has been to provide more cost effective (less expensive) and easier weed control for farmers. No significant difference between HT and conventional crops occurs in most cases. Only in a few examples when certain weeds were difficult to control with selective herbicides did the adoption of HT crops associated with the switch to broad-spectrum herbicides result in better weed control and higher crop yields (e.g., HT soybeans in Romania, HT maize in Argentina).

> Insect resistant Bt crops: The yield-increasing effects differ strongly, from 0 to nearly 40%. Yield effects of Bt cotton are highest in Argentina and India. Explanation are that conventional methods of pest control were less effective due to reasons such as less well developed extension and advisory services, insecticide quality, insecticide resistance, and correct choice of products and timing of sprays. For Bt maize, yield increases are generally at a lower magnitude. In the USA, Bt maize is used mainly against the European corn borer, which is not often controlled by pesticides. In Argentina and South Africa, mean yield effects are higher because pest pressure is more severe than in temperate climates.

Varying factors such as legal frameworks, costs for seeds, adoption of varieties to different regions, pest or weed pressure and conventional pest management influence the outcomes achieved by cultivation of GM crops. For example, yield increases through the introduction of Bt maize were around 4% on average, varying across different countries. In Spain for example, the yield increases due to Bt maize were approximately 6% on average, in Germany 12%, and 25% in South Africa compared to conventional maize varieties (Kaphengst et al. 2011, p. 3 and p. 65). Overall, yields depend on a wide range of factors that "go far beyond the mere choice between GM and conventional crops" (Kaphengst et al. 2011, p. 66). As an example for co-influencing factors, the introduction of herbicide-tolerant soybeans in Romania was associated with changes in the production management. Therewith, it is not clear whether the distinct yield increase results from the usage of GM varieties or could also have been reached solely by production management improvement (Meyer 2012).

Studies of GM crop effects at farm level are often based on comparing the performance of adopters and non-adopters of GM crops. Such with-without comparisons can be associated with a selective bias. On the one hand, if adopting farmers are more skillful than their non-adopting counterparts, the net technological impact can be overestimated. On the other hand, if the GM crop is adopted only by farmers under specific conditions such as high pest pressure, net impacts may be underestimated (Qaim 2009). A meta-analysis of studies on Bt cotton comes to the result that economic returns are highly variable over years, farm type, and geographical location. They depend on initial practices, pest infestations, seed costs, and other attributes of farmers and farm production so that findings cannot be generalized. Most often, institutional and marketing arrangements for supplying the technology and marketing the product may be the single most important determinant of Bt impact at the farm-level (Smale et al. 2006).

Another issue broadly discussed in the context of 1st generation GM crops is the *risk of pest and weed resistance*. The refuge strategy has been the primary approach used worldwide to delay pest resistance to Bt crops and has been mandated in the USA, Australia and elsewhere (Tabashnik et al. 2013). Typically the refuge is an area of conventional crop not expressing the Bt trait planted within a certain distance of the Bt field so that the rare resistant pest surviving on Bt crops will mate with the relatively abundant susceptible pest nearby (Head, Greenplate 2012). Additionally in the last decade, first generation Bt crops producing one Bt toxin were increasingly replaced by second generation Bt crops, named pyramids, that produce two or more distinct Bt toxins active against a particular pest. This is based on the assumption that selection for resistance to one Bt toxin does not cause cross-resistance to other toxins in the pyramid, so that insects resistant to all toxins are extremely rare (Tabashnik et al. 2013).

Field-evolved resistance associated with reduced efficacy of Bt crops has been reported for five major target pests in 8 countries around the world, parallel to the increased area planted to Bt crops. Resistance can evolve in as few as 2 years under the worst circumstances; however, under best circumstances, efficacy can be sustained for 15 years and more (Tabashnik et al. 2013). A common pattern for resistance development is continuous maize cultivation and continues use of one specific Bt trait. Therefore, it is proposed to use a greater diversity of practices such as crop rotation, cultivation of different Bt events and seed mixtures and alternating cultivation of non-Bt crops with insecticides (Gassmann et al. 2012).

Heavy reliance on a single herbicide – glyphosate – in different GM crops has placed weed populations under progressively intense selection pressure (Owen 2008; Duke, Powles 2009). Glyphosate-resistant weeds have now been found in 18 countries worldwide, with significant impacts in Brazil, Australia, Argentina and Paraguay. For example, glyphosate-resistant Palmer amaranth became since the mid 2000 a severe problem in cotton cultivation of the southeastern United States (Gilbert 2013). The Weed Science Society of America lists 22 glyphosate resistant weed species, and an increasing area (estimated 20-25 million ha) is impacted by glyphosate-resistant weeds. Farmers began to mix glyphosate with effective doses of different herbicides (Powles 2008). An assessments estimates that herbicide-tolerant GM crops have led to a 239 million kilogram increase in herbicide use in the United States between 1996 and 2011 (Benbrook 2012). In reaction to the problems, Monsanto and other biotechnology companies are developing new herbicide-resistant GM crops that work with different herbicides, which they expect to commercialize within a few years (Gilbert 2013). Critics on this strategy are that GM crops with stacked heribicide resistance are likely to increase the severity of resistant weeds, that they will facilitate a significant increase in herbicide use, and that the short-term fix provided by the new traits will discourage public research and extension in integrated weed management (Mortensen et al. 2012).

Another challenge can be the *emergence of secondary pests* because toxin of Bt crops has specific activities against a restricted number of insects and the insecticide treatments (with broad spectrum of targeted insects) are reduced with the introduction of Bt crops. The emergence of minor pest becoming major pests is reported for Bt cotton in China, India und the USA. While there are numerous studies which assessed the impact on pests not-targeted by Bt cotton at field level, there is little data concerning the impact at the regional level (Bergé, Ricroch 2010). The underlying mechanism well known in crop protection is that when a primary pest is successfully targeted than other species are likely to rise in its ecological place. On the one hand, the development of new transgenic crops with a broader spectrum of insect-resistance is proposed. On the other hand, the introduction of biological control methods and changed cultivation are discussed as approaches to fight against the damage of secondary pests on Bt crops (Bergé, Ricroch 2010).

On international level, *research and development of new transgenic crops* are targeted on issues such as (Stein, Rodriguez-Cerezo 2009; Godfray et al. 2010):

> Herbicide tolerance (new herbicides such as 2,4-D)
> Pest, disease and virus resistance (e.g., sucking insects)
> Abiotic stress tolerance (e.g., drought tolerance, salinity tolerance)
> Improved food or feed quality (e.g., improved fatty acid profile, high lysine content)
> Improved processing and storage (e.g., extended shelf life of tomato)
> Improved crops for industrial use
> Nitrogen fixation
> Increased photosynthetic efficiency

The latter two are assessed as long-term targets which will need more than 20 years (Godfray et al. 2010). The reachability of these long-term claims is contested. In regard to GM crops with improved nitrogen use efficiency (NUE), it is argued that such GM crops are difficult to produce because available genes for NUE are restricted and these genes interact with other plant genes in complex ways influencing other plant properties (Gurian-Sherman, Gurwick 2009). Similar arguments are applied for GM plants with drought tolerance: Some individual genes can affect genetically complex traits such as drought tolerance. However, such GM crops may not be enough to substantially reduce crop losses in the real world, where drought can vary in severity and duration, because any given engineered gene is likely to address only some types of drought to a limited extent (Gurian-Sherman 2012).

The six leading developers – BASF, Bayer, Dow, DuPont Pioneer, Monsanto and Syngenta – spend about US$ 3 billion yearly on the research and development of GM seeds. The number of new GM seeds that any company can afford to develop is relatively small because the cost of development for each GM product is between US$ 135 and 200 million (Raybould, Poppy 2012). In the next years, a significant global increase in the number of individual commercial GM events, from around 30 today to over 120 commercial GM events by 2015, is estimated. Most of the existing events in commercial GM crops were developed by private companies from the USA or Europe, with broad authorization of their products in key export markets (in particular the EU and Japan). However, by 2015 about half the events in commercial GM crops are expected to come from national technology providers in Asia (and Latin America), designed for their domestic agricultural markets. Therewith, isolated foreign approval will occur, and incidents due to low-level presence of unapproved GM material in imports of crops or processed foods from these countries are very likely (Stein, Rodriguez-Cerezo 2009, p. 10).

GM research and development profit from the improvements of DNA sequencing techniques which nowadays enable to sequence whole plant genomes at constantly shrinking costs (Lusser et al. 2012; Thudi et al. 2012).

Conventional breeding approaches and principles remain essential and important also in the context of the breeding of transgenic crops. GM technologies will not replace existing, established techniques, but they represent tools which can support conventional breeding and increase the breeding success (Bruce

2011). Conventional breeding led to most of the genetic improvement of crop plants in the past and will certainly continue to play a major role in crop improvement programs (Jauhar 2006).

Concerning public acceptance, opinions towards GM crops vary globally. In America, Asia and South Africa, the GM approach is much more accepted than in Europe (Bruce 2011). 70% of the European citizens agree with the statement that genetically modified food is "completely unnatural" while the percentage of GM advocacies only accounts for 23% (Meyer 2012). Public opinion is an important background for the debates about GMO regulation (Box 4).

Box 4

EU regulation of GM crops and food

Harmonised GMO regulation in the EU goes back to the year 1990, when Directive 90/220/EEC on the deliberate release of GMOs into the environment and Directive 90/219/EEC on the contained use of genetically modified micro-organisms came into force. The legislation has in the meantime been revised and updated (Lusser et al. 2011, p. 75).

Directive 90/220/EEC has been replaced by Directive 2001/18/EC. Additional legislation was introduced 2003 with Regulation EC/1829/2003 on genetically modified food and feed (Waigmann et al. 2012). Key points of the revised regulation are strengthening of the precautionary principle, limited approvals for ten years, post-marketing monitoring (general surveillance and case-specific monitoring), and technology-based labeling.

Besides the GMO definition the legislation includes lists defining "(i) techniques which give rise to GMOs, (ii) techniques which are not considered to result in GMOs such as in vitro fertilization, natural processes like conjugation, transduction, transformation and polyploidy induction and (iii) techniques of genetic modification which are excluded from the GMO legislation" (Lusser, Cerezo 2012, p. 8).

Difficulties with the implementation of the legislation continue. The current regulatory approval system is regarded as expensive, time-consuming and inappropriately focused on the technology rather than the product (EASAC 2013, p. 28). In the last years, only one new approval was awarded. Beside the conflicts in the approval procedure, 8 Member States used the safeguard clause of Directive 2001/18/EC to introduce bans on the cultivation of authorized GM crops (EASAC 2013, p. 28).

An evaluation of the EU legislative framework was launched in December 2008. Two consortia carried out the evaluation out the evaluation of the EU legislative framework in the field of GM food and feed and of the EU legislative framework in the field of cultivation of GM crops respectively (Lusser et al. 2011, p. 75). In 2010, the Commission has proposed an opt-out clause which would allow Member States prohibit the cultivation of GM crops on national, regional or local level with socio-economic reasoning (EC 2010b).

Breeding of cisgenic and intragenic crops

The classical approach of genetic modification of crop plants describes the transfer of a gene of interest from any organism to a plant that shall be improved for a particular trait. The source of the gene can be diverse, for example a plant of the same species, an unrelated different crop plant or a completely different organism, like a bacterium (ISAAA 2010). There are common concerns that by using this approach, alien genes are introduced to crop species that could never be introduced to a plant by using natural crossing methods and might have unexpected and unknown effects on the plant development and also the environment (Bruce 2011). Attending these doubts the cisgenesis-/intragenesis-approach has been developed. The Some authors equalize the terms cisgenesis and intragenesis and use them interchangeably, describing one and the same approach (Schouten et al. 2006). Contrary there are clear distinctions of the two terms described in other literature (EFSA 2012).

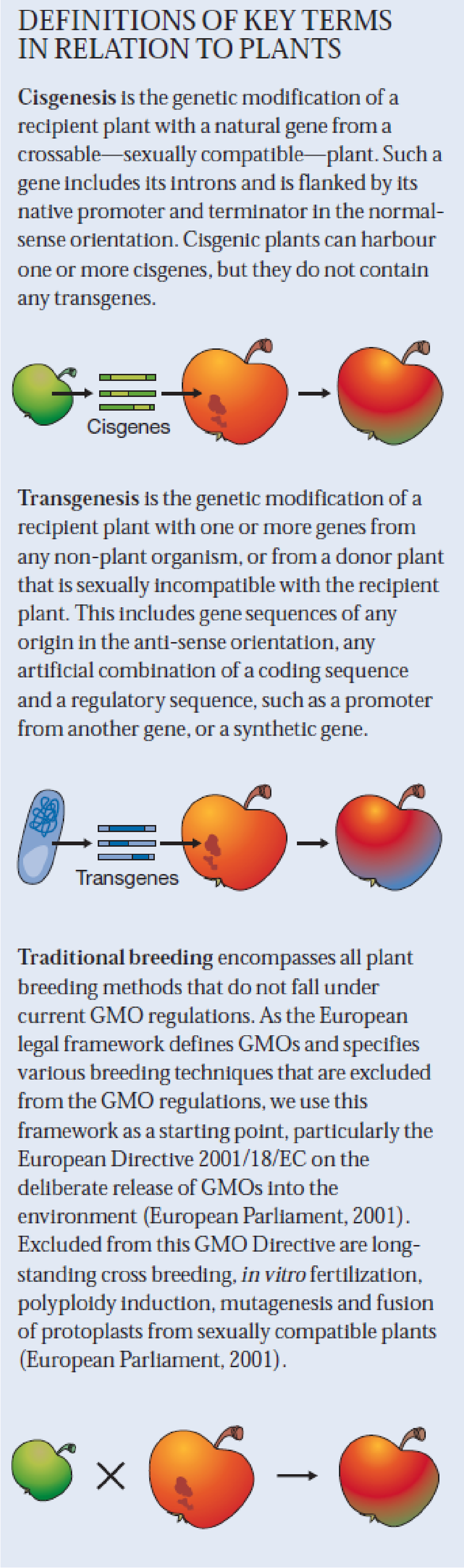
Cisgenic modification of plants uses the same techniques like classical GM approaches. The main difference lies in the source of the gene that shall be transferred. A cisgene origins from the same species or a closely linked plant species that is naturally combinable with the plant variety which shall be improved. This means that the gene or the trait respectively that shall be transferred from one plant to another could theoretically also be transferred using conventional breeding methods. The main idea behind the cisgenesis approach is to identify, isolate and transfer particular genes in a directed manner to speed up the breeding process. The main applications for cisgenesis are resistance and quality breeding.

Intragenesis goes further. On the one hand the same gene pool of the bred crop plant is used, but on the other hand genetic elements within the DNA sequence of a gene are modified. Intragenesis offers more options for modifying gene expression and trait development as genetic elements can be recombined within the DNA sequences. Therefore it represents an applicable technique for gene silencing, the targeted turning-off of particular genes (Müller-Röber et al. 2013, pp. 39-93; EFSA 2012). The EFSA GMO Panel argues that there are similar hazards associated with cisgenic and conventionally bred plants, while there can be novel hazards associated with intragenic and transgenic plants (EFSA 2012).

Figure 18 summarizes the cisgenesis, transgenesis and conventional breeding approach with their main characteristics. The cisgenic/intragenic modification approach falls under the current European GMO legislation (Directive 2001/18/EC) because the available methods for cisgenic modification of plants also artificially modify the genetic makeup of a plant (AGES 2012, p. 13).

Scientists see big potential in cisgenic approaches for crop improvement and there are studies that clearly differentiate between classical transgenic modification and cisgenesis. Schouten et al. (2006) equalize the cisgenic modification approach and conventional plant breeding. They point out that cisgenesis approaches do not alter the gene pool and provides no additional traits. Therefore, there are no changes in the genome that could not have occurred through traditional breeding or natural gene flow. On the other hand there are also contrary

Figure 18: Definitions of cisgenesis, transgenesis and conventional breeding



DEFINITIONS OF KEY TERMS
IN RELATION TO PLANTS

Cisgenesis is the genetic modification of a recipient plant with a natural gene from a crossable—sexually compatible—plant. Such a gene includes its introns and is flanked by its native promoter and terminator in the normal-sense orientation. Cisgenic plants can harbour one or more cisgenes, but they do not contain any transgenes.

Transgenesis is the genetic modification of a recipient plant with one or more genes from any non-plant organism, or from a donor plant that is sexually incompatible with the recipient plant. This includes gene sequences of any origin in the anti-sense orientation, any artificial combination of a coding sequence and a regulatory sequence, such as a promoter from another gene, or a synthetic gene.

Traditional breeding encompasses all plant breeding methods that do not fall under current GMO regulations. As the European legal framework defines GMOs and specifies various breeding techniques that are excluded from the GMO regulations, we use this framework as a starting point, particularly the European Directive 2001/18/EC on the deliberate release of GMOs into the environment (European Parliament, 2001). Excluded from this GMO Directive are long-standing cross breeding, *in vitro* fertilization, polyploidy induction, mutagenesis and fusion of protoplasts from sexually compatible plants (European Parliament, 2001).

Source: Schouten et al. (2006)

opinions that, using the currently available transformation methods, it is not possible to produce cisgenic plants that only carry the wanted cisgene without any further modifications (AGES 2012, p. 24).

There are different studies describing the successful application of the cisgenesis approach in different types of crop plants, such as apple, barley, vine and potato. Especially trees represent an attractive target for cisgenic modifications because of the decreased time for cultivar development by using this technique. Cisgenesis is mainly applied in the Netherlands, USA and New Zealand. Furthermore there are European institutes in Switzerland (Swiss Federal Institute of Technology (ETH) Zürich) and Germany (Julius Kühn Institute (JKI), Institute for Breeding Research on Horticultural and Fruit Crops, Dresden-Pillnitz) working on cisgenic/intragenic apples. However, the number of published studies that provide detailed information about the cisgenic approach is relatively low which indicates that cisgenesis is not a broadly implemented technique. The main challenge that comes up is the further revealing and characterisation of genes, their specific functions and how they interact amongst each other. Especially the potential interaction of genes still represents one of the main bottlenecks of the cisgenesis technology as many traits result from gene interactions. In the case of resistance breeding, it is furthermore important to introduce a combination of resistance genes to ensure that resistances are not broken rapidly.

New plant breeding techniques

Besides the cisgenesis-/intragenesis-approach, several other new plant breeding techniques are in the pipeline, being intensively researched and tested and may play important roles for plant breeding in the near future. The following techniques are described as most important (AGES 2012, pp. 37-61; Lusser et al. 2011; Lusser et al. 2012; Müller-Röber et al. 2013, pp. 39-93; ZKBS 2012):

> *Zinc finger nuclease (ZFN) technology* (ZFN-1, ZFN-2 and ZFN-3): The ZFN techniques allow the targeted induction of mutations in a genome, including insertion of large DNA segments and formation of deletions. Zinc finger nucleases are chimeric proteins which binds to a specific nucleotide sequence in double-straded DNA and produce double-strand break. Some techniques (ZFN-1, ZFN-2) involve the generation of a GMO in an intermediate step, from which progency that no longer carry the genetic modification are subsequently selected. With ZFN-3, the DNA stretch is inserted into the plant genome.

> *Oligonucleotide directed mutagenesis (ODM)*: This technique involvesthe transfer of oligonucleotides into a cell to produce a site-specific mutation at a certain sequence and is based on the sequence-specific interaction of the oligonucleotide with its target sequence in the cell genome (gene targeting). The result can be the introduction of a new mutation (replacement of one or few base pairs), the reversal of an existing mutation or the induction of short deletions.

> *RNA-dependent DNA methylation (RdDM)*: With the RdDM technique it is possible to turn off the expression of specific genes without altering the DNA sequence of the organism. The technique is based on the targeted methylation of the respective pormotor which is thereby inactivated. Genes encoding RNAs (which are homologous to promotor regions) are delivered to the plant cells by transformation methods and involve, at some stages, the production of a transgenic plant. The change in the methylation pattern of the promotor, and therefore the desired trait, will be inherited by the following generation, but the effect isn assumed to decrease through subsequent generations.

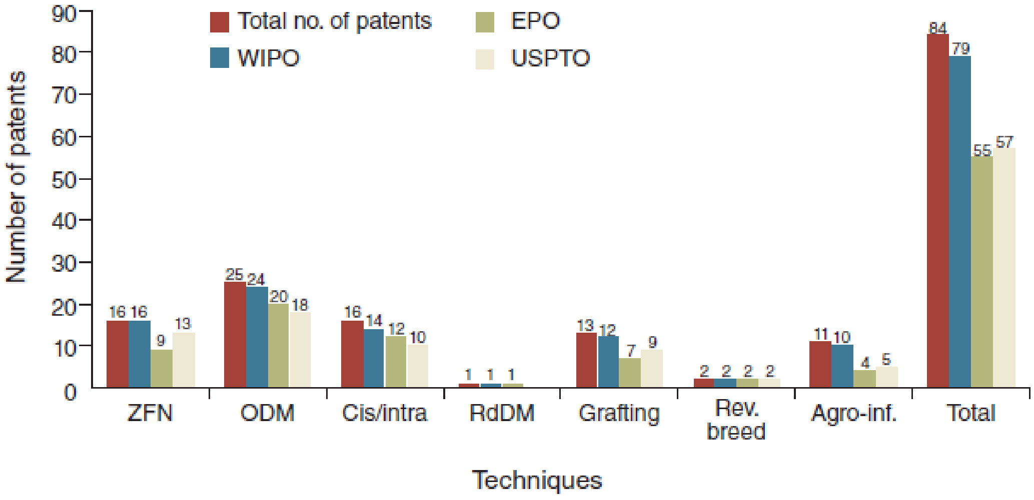
> *Grafting (on GM rootstock)*: Grafting is a classic technique whereby an above ground vegetative component (shoot or scion) is attached to a rooted lower component (rootstock). The two parts grow together and the result is chimeric organism with improved cultivation characteristics. When a non-GM scion is grafted onto a GM rootstock, leaves, stems, flowers, seeds and fruits do not carry the genetic modification.

> *Reverse breeding*: The order of events leading to the production oif a hybrid variety is reversed. The reverse breeding technique makes use of transgenesis to suppress meiotic recombination. In subsequent steps, only non-transgenic plants are selected. The result are two homozygous parental lines for hybrid production.

> *Agro-infiltration*: Plant tissues, mostly leaves, are infiltrated with a liquid suspension of Agrobacterium spp. (by rubbing, injection or applying vacuum pressure). Therewith, transgenes are transferred locally and can lead to a stable integration in the genome of somatic cells. Agro-infiltration can be used to screen for plants with valuable phenotypes. For instance, agro-infiltration with specific genes from pathogens can be used to evaluate plant resistance. The resistant plants identified will not be transgenic as no genes are inserted into the genome. In the case of "floral dip" (immersion into a suspension of Agrobacterium carrying a transgenic construct), the transgene can be integrated stably into the genome, and a transformed plant is obtained.

In the last 10 years there has been an increase of publications describing the use of the techniques. In 2011, 187 publications were identified and the number is growing quickly. Europe is leading the research field with 45% of the publications concerning their geographical distribution, followed by the North America with 32% (Lusser et al. 2011, p. 6). Patents also play an important role in context with modern biotechnologies. Figure 19 summarizes the actual number of patents that are hold or applied at the main patent offices.

Figure 19: Patents on new plant breeding technologies at EPO and USPTO, and PCT applications administered by WIPO



Note: "Patents" refer to both granted patents and patent applications until February 2009 and each patent represents all members of its family.
EPO – European Patent Office
USPTO – US Patent and Trademark Office
WIPO – World Intellectual Property Organisation

Source: Lusser et al. (2012)

In Europe, as well as in North America, the broad majority of patents is hold by the private sector. A survey of responsible persons from breeding companies found that all of the modern techniques are in commercial use, at least in some big companies (Two to four out of 17 interviewees). According to the experts opinion, ODM, cisgenesis/intragenesis and agro-infiltration are the most important modern techniques at the moment and the crops developed with these techniques have reached field testing. ZFN technology, RdDM, grafting on GM rootstocks and reverse breeding are less used techniques in practical breeding programmes (Lusser et al. 2011, p. 7).

The new plant breeding techniques are "tiptoeing" around transgenics (Waltz 2012). Uncertainties regarding the regulatory status (crops derived by these techniques will be classified as GMOs or not) worldwide are seen as a constraining factor for the adoption (Lusser et al. 2012). Regulatory costs for plants classified as GMOs are much higher than those for the registration of non-GMO plants (Lusser et al. 2011, p. 5). Against scientific assessement, it is argued that consumer concerns are not restricted to the inserted transgene and its presence in the plant, but also includes concern about unintended effects that could occur as a result of insertional mutagenesis. The differences between targeted approaches and the older, less precise methods of genetic modification may be lost in public awareness (Waltz 2012).

The new techniques pose new challenges for detection. Availability of detection methods is a mandatory requirement for GMOs under the EU regulation. Current standard methods for GMO detection are largely based on DNA and rely on PCR (Polymerase Chain Reaction). When the resulting genetic modification cannot be distinguished from those produced by conventional breeding techniques or by natural genetic variation, it is not possible to develop detection methods that provide unambiguous results. For some of techniques detection seems to be possible, provided some prior information is available. Only for ZFN-, cisgenesis/intragenesis and the floral dip variant of agro-infiltration, a detection is possible (Lusser et al. 2011, p. 10; Lusser et al. 2012).

5.3.6. Breeding in organic farming

Organic farming is practiced in more than 130 countries of the world. Organically cultivated land accounted for 5.4 % of the agricultural area in the 27 EU member states in 2011 (Chapter 4.1.4). As organic farming follows principles to enhance agricultural sustainability, also the seeds produced for organic crop cultivation are subject to requirements that have to be fulfilled to make them suitable for organic farming systems. The accounts of organic farming regarding plant breeding are defined by the EU-Regulation 2092/91. Until 2004, organic farmers could sow conventionally produced plant material, but with some restrictions: The parent plants of annual crops had to be grown for at least one generation under organic conditions, parents of biannual and perennial varieties had to be grown for at least two years under organic conditions (Wyss et al. 2001, p. 2). This came along with the general question and the doubt weather these varieties truly fulfil the needs of organic plant production.

Since 2004, organic producers have to use explicit organic seed or planting material for crop production. As plant breeding in general mainly developed in response to the demands of intensive agriculture over the last 60 years, many of the available organic seeds origin from conventionally bred plant material. It is important for organic plant production that the production methods by which the seeds have been produced are compatible with the principles for organic farming. As there has been rapid progress in the development of plant breeding techniques there is no fully comprehensive valuation of breeding techniques by now.

One major principle for organic farming and thereby plant breeding for organic plant production is to maintain the integrity of plants. This mainly aims towards those techniques that artificially disrupt the genetic makeup of a plant or disturb or manipulate its natural growth, development and propagation. Furthermore, this principle excludes techniques which are used to do wide crosses between unrelated species in order to overcome natural crossing barriers (Acquaah 2007, p. 468 and 469; Lammerts van Bueren et al. 1999, p. 6; Wyss et al. 2001, p. 22 and 23). Therefore, techniques like protoplast fusion, mutatagenesis or *in vitro* propagation are not suitable for organic plant breeding (Messmer et al. 2012). For organic seed production it is also important that the seeds can be reproduced by the farmer himself which accompanies with the decline of the hybrid breeding method. Techniques that only represent diagnostic tools, like marker-assisted selection, are suitable for organic seed production (Acquaah 2007,

p. 469). Additionally, there are clear standards for organic plant production. Plants produced by genetic modification techniques are subject to the European regulation No. 834/2007 and are thereby strictly prohibited for organic agriculture. This regulation also requires that the seeds used for plant production in organic farming must be produced out of organically generated plant material (Messmer et al. 2012).

The breeding goals of organic plant breeding differ from those for conventional breeding. Organic varieties must be well adapted to organic conditions and comprise high resistances and tolerances to biotic and abiotic stresses, including high adaptation to local climate and nutrient dynamics as well as a high nutrient efficiency and a high yield stability and storability of the product (Wyss et al. 2001).

In Europe, the current status of organic breeding is highly heterogeneous. While specialised and organised breeding for organic farming does not exist in some parts, countries like Germany are making great efforts in developing organic breeding in order to provide seeds for organic farming systems. The German national variety list comprises around 15 organic cereal and 50 vegetable varieties (Peter Wilbois, personal communication 2013).

The current growth in the organic production sector leads to an increasing demand for organic seeds. Plant breeding on the organic sector will need more time and more money to be raised (Lammerts van Bueren et al. 2007; Messmer et al. 2012). Furthermore, there are concerns that the breeding success will not cover the increasing demand for a rise of productivity when new emerging technologies are categorically declined. Therefore, it is important to define clear criteria based on which new promising technologies can be assessed whether they really fit in or violate the principles of organic plant production (Messmer et al. 2012).

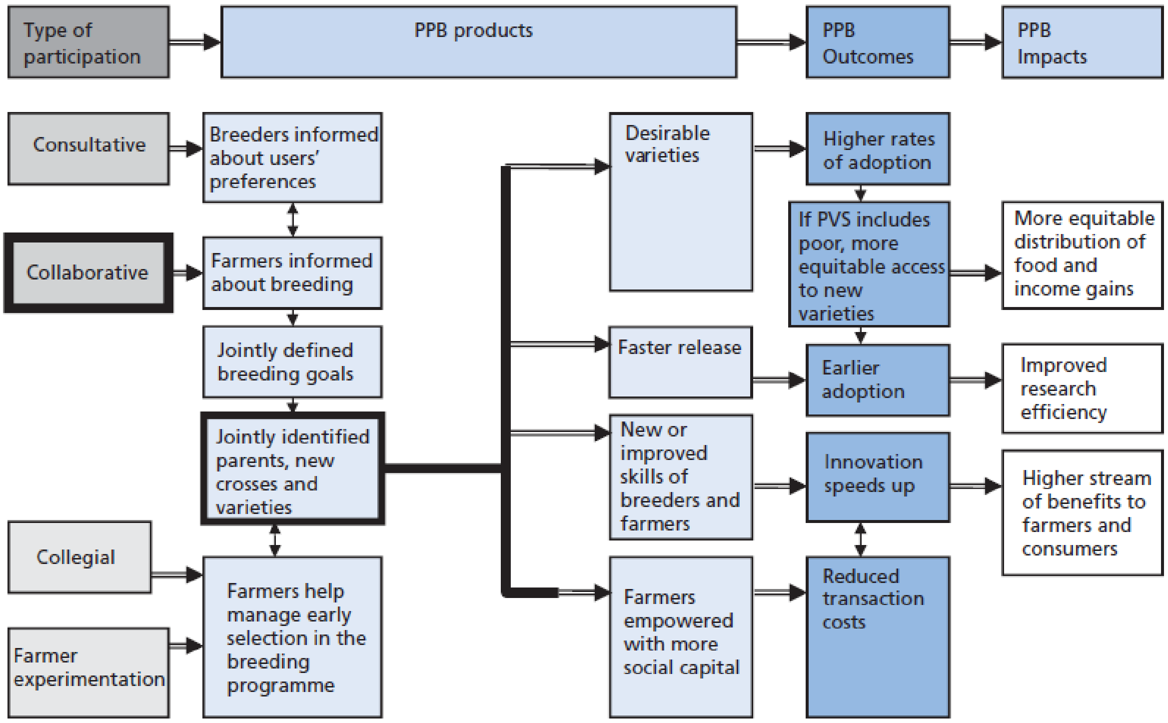
5.3.7. Participatory plant breeding

Participatory plant breeding (PPB) describes the approach to involve collaborations between plant breeders and farmers in breeding programs. Thereby, farmers are involved as cooperating partners in all stages of a plant breeding program whereas in conventional breeding programs only professional plant breeders or scientists are responsible for the creation of a new plant variety. The concept of PPB evolved in the 1980s and was originally invented to address the needs of small-scale farmers in developing countries (Vernooy et al. 2009, pp. 617-626).

The aim is to involve the individual demands and experiences of the farmers in the breeding process, to create varieties that are well adapted especially to marginal regions. The farmer involvement in the breeding program can take different forms and ranges from only interviewing farmers in the planning phase of a breeding program to fully involve them in processes of generating initial genetic variation, selection of favourable genotypes and maintenance of new cultivars (Kotschi 2010). Figure 20 shows the different levels of PPB with different impacts on the outcomes.

Until now, PPB has rarely been adopted to countries with good agricultural conditions. These regions are dominated by classical breeding programs conducted by professionals without farmer participation in decision steps of the breeding program. PPB mainly plays a role in marginal regions in developing countries which are dominated by small-scale farming systems. Formal commercial seeds are standard in high-input agricultural systems with more or less uniform environments, but have a low spread in extensive small-scale farming systems (Chapter 5.4.2.).

Figure 20: Impact pathways for participatory plant breeding (PPB)



Source: Ashby (2009)

Different constraints limit the widespread of formal commercial seeds in low-input systems, both on the supply side and on the demand side. From the supply side, the major limiting factors are the low adoption of the varieties to the marginal high heterogeneous environments and the relatively high production costs for plant material. The demand side is on the one hand restricted by anticyclical demands for seeds. This means that in years of high market prices for the produce at harvest the purchase of seed for the next planting is stimulated. This leads to an oversupply in the next year and prices drop. Furthermore, variable cash incomes from crop sales depress the investments of farmers in quality seeds (Almekinders et al. 2007).

It is assumed that seed supply in marginal regions is best improved by strengthening local seed systems, rather than by replacing local varieties with seeds from the formal sector. This is because farmers' selection practices, seed production and handling are often well-developed in local seed systems (Almekinders et al. 1994).

The PPB approach was invented to face the lack of availability of seeds and to improve crops grown in marginal low-input environments. Directly involving farmers in the decision making of breeding programs has the aim to produce varieties that are well adapted to their special cultivation area. By 2009 there were around 100 PPB programs worldwide by diverse institutions (PRGA 2009).

It is difficult to assess the general impact of PPB on variety improvement and production in general as insignificant results are rarely reported (Walker 2008). However there are several studies over the last two decades reporting the successful application of PPB programs in different marginal regions. For example, five successful PPB programs were reported by the "Centre of Arid Zone Studies" (CAZS), an organisation of the Indian Council of Agricultural Research (ICAR). Using PPB, improved rice varieties could be generated for the rainfed uplands of eastern India as well as improved maize varieties for eastern India and the hill areas of the western state of Gujarat. Furthermore, improved rice varieties could be generated for the high-altitude hills in Nepal. The "International Center for Agricultural

Research in the Dry Areas" (ICARDA) could also arrange significant crop improvement and variety adoption for barley in Syria, Jordan, Egypt, Eritrea and Yemen. One elite line, Zanbaka, was submitted to the official system and was rejected to insufficient adoption to the cultivation area. It was then included in PPB field trials and was improved under respect of the farmers' preferences. In 2006, Zanbaka has spread from the "participatory breeding" villages to over five thousand hectares in Syria in several provinces (Walker 2008). The fact that PPB programs are strongly supported by numerous public institutions worldwide indicates the general significance of PPB and the expectance of experts that the technique represents a powerful tool for crop improvement and food security.

Until now, progress of PPB programs has been faster for cereals than for other crops such as roots, tubers and pulses. Especially self-pollinated crops represent ideal candidates for PPB compared with open-pollinated crops as selection and seed production for allogamous species requires much more efforts from the farmers than for autogamous species (Walker 2008).

From a PPB advocating point of view, there are different constraints that have to be overcome to increase the importance of farmer participation in plant breeding programs and to make PPB an institutional part of seed production. A main problem for adoption of PPB is the general attitude of scientists, professionals and political decision makers assuming that PPB is one of two contrasting types of plant breeding, rather than seeing participatory plant breeding as an additional option for crop improvement (Ceccarelli et al. 2009). The process of privatising plant genetic resources represents another critical issue. Therefore, public investments in plant breeding should be made in order to regain control over crop variety development of the public sector. Furthermore, national seed laws have to be amended and decentralised in a way that local varieties do not fall under the strict registration criteria that have to be fulfilled for variety registration.

Moreover, there are recommendations that claim a separation of plant breeding and seed supply, disposing the initial breeding procedure and research to public programs, whereas seed production and distribution should be undertaken by companies of the private sector. This could contribute to a wider range of well adopted varieties and a better seed supply for farmers (Kotschi 2010).

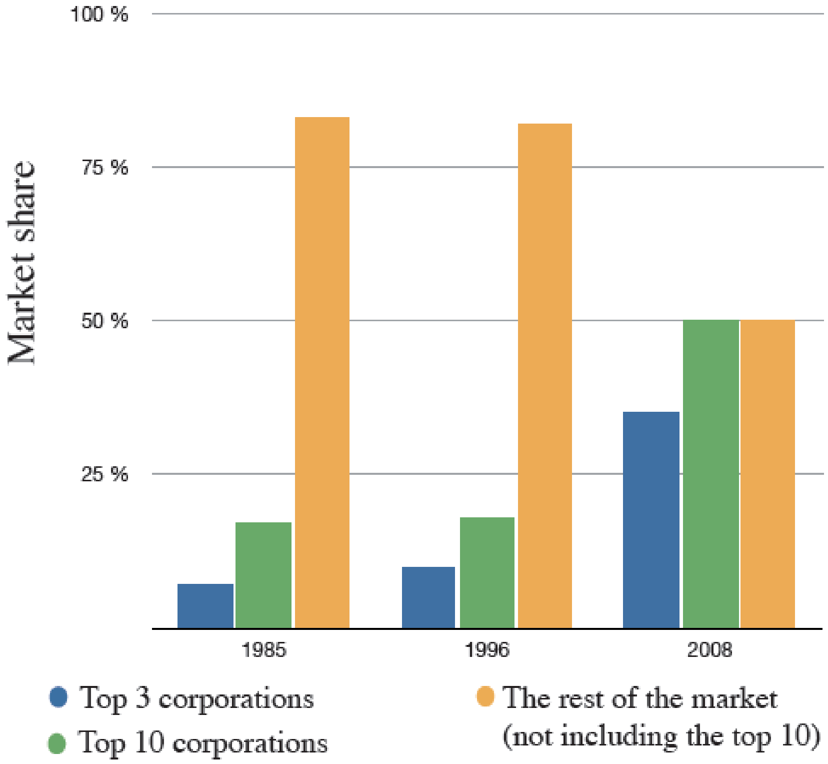
5.4 Seed industry

Crop improvement by plant breeding approaches is undertaken in both the private and the public sectors and can be divided into commercial and non-commercial enterprises (Acquaah 2007, p 30; Mulle, Ruppanner 2010). The private sector is represented by private companies that produce formal seed to realise monetary profits. In contrast the public sector is represented by institutions that are not profit-orientated doing research on the field of plant breeding (Acquaah 2007, pp. 30-32).

5.4.1. Commercial seed market

The "International Seed Federation" (ISF) estimates the value of the global seed market at approximately 45 billion US$ at the moment. This number only represents revenues from commercial seed sales and does not include informal, farm-saved seed (http://www.worldseed.org/isf/seed_statistics.html). The most important part of the seed market is represented by cereals (around 36%), followed by horticultural seeds (around 21%) and oilseeds (around 14%) (Ceddia, Cerezo 2008, p. 6). The international commercial seed market is in a concentration process which means that increasing market shares for seeds are allocated to a small number of major corporations (Figure 21).

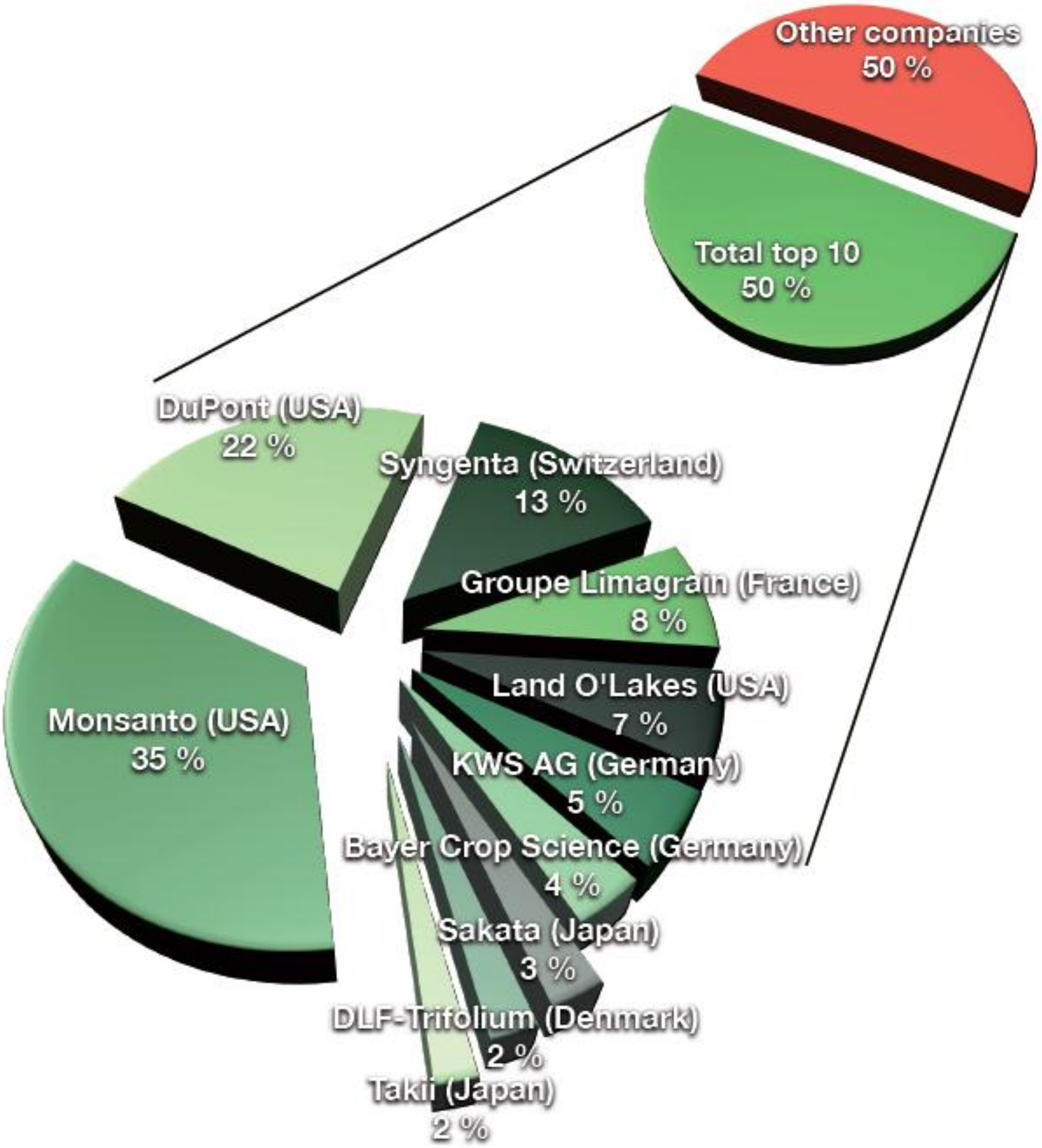
Figure 21: Evolution of market concentration in the global seed industry, 1985-2008



Source: Mulle, Ruppanner (2010)

The market share of the ten top seed production corporations have increased from less than 20% in 1985 to 50% in 2008 (Figure 21). In 2008, the three top corporations owned 35% of the market and the top five accounted for 42%. The skyrocketing of the market concentration since 1996 can be traced back to the appearance of a series of big mergers that affected the whole agro-industry (Mulle, Ruppanner 2010). Figure 22 displays the ten most important companies for the seed market.

Figure 22: Top 10 corporations' market share of the global seed market



Source: Mulle, Ruppanner (2010)

5.4.2. Non-commercial seed market

The non-commercial seed market, also named with "saved seeds", is part of the traditional agriculture and/or crop production without strong link to national or international food supply chains. Non-commercial seeds originate from harvested seeds shared among and re-sown by farmers (Hu et al. 2009; Mulle, Ruppanner 2010). In 2006, the non-commercial seed market was estimated to account for 30% of the total world seed market (Ceddia, Cerezo 2008, p. 6).

It is estimated that about 80 percent of food production is delivered by smallholding farmers that mainly use informal seed of the non-commercial seed sector. Most of the crops that are cultivated in developing countries are not of commercial interest to the private sector but constitutes important food security crops (FAO 2011c). In Africa, about 80% of the cultivated seed is informal. The remaining 20% formal seed are exclusively composed of hybrid maize and ornamental seed (Wekundah 2012). Whereas informal seed play an important role for small-scale farmers in marginal regions, they play a minor role in developed countries with high-input farming systems (See chapter 5.4.1).

5.4.3. Plant breeding and intellectual property rights

Before a new variety can be released to the market and be sold to farmers, it has to pass through an extensive registration process. A new registered variety represents the result of an extensive and expensive breeding program undertaken by a plant breeder and is thereby subject to the plant breeder's intellectual property (IP) (Somersalo, Dodds 2009, p. 630). The two most important approaches to protect intellectual property rights (IPR) are plant breeders' rights (PBR) and patents. Their application differs depending on the legal situation in the particular country.

Plant breeders' rights

The international system to protect plant breeders' rights (PBR) is the UPOV (International Union for the Protection of new Varieties of plants) and their "plant variety protection" (PVP). The intergovernmental organization UPOV was established by the "International Convention for the Protection of New Varieties of Plants". The UPOV Convention was adopted in Paris in 1961 and it was revised in 1972, 1978 and 1991. The Convention provides a *sui generis* form of intellectual property protection which has been specifically adapted for the process of plant breeding and has been developed with the aim of encouraging breeders to develop new varieties of plants (http://www.upov.org/portal/index.html.en). In 2004 the UPOV had 58 member countries.

The UPOV Convention regulates that new produced varieties can only be commercialised by the seed producer. It sets forth the minimum of protection a country has to guarantee producers of new plant varieties (Somersalo, Dodds 2009, p. 631). In variety registration the essential requirements for a new variety are:

> Distinctness
> Uniformity
> Stability

A new variety must be clearly distinct from other existing varieties in at least one trait, has to be uniform and homogenous, and must be feasible for stable reproduction without prohibitive aberration in its trait expression or performance respectively (Richter 2012). If a cultivar could pass this testing procedure, it is registered in the particular variety list of the country and ready for market entry.

In the EU, the legal frame for variety production, protection and placing on the market of new plant varieties is defined by the "Community Plant Variety Office" (CPVO) which is based in France. The CPVO lists all current information about all plant varieties that are registered for marketing in the EU including all varieties listed in the national variety lists. The protection of new varieties is regulated the Council Regulation (EC) No 2100/94 of 27 July 1994 on Community plant variety rights and comprises a variety protection for at least 25 years for "regular" plant varieties, for vine varieties and tree species for 30 years (EC 2013).

Patents on plants

In most countries patenting of plants and inventions directed to plants or plant products (e.g. seeds) is not eligible. However, countries like the United States or Australia entitle enterprises to make claims to a time-limited right to exclude others from the use of plant material, as long as the legal criteria for patentability are met. Once a patent has been granted the protection usually lasts for 20 years since the effective filing date.

In the EU, patent issues are controlled by the "European Patent Convention" (EPC) and administered by the "European Patent Office" (EPO). Historically, each European country had its own national patent laws until the adoption of the Directive 98/44/EC (effective in all European Union member states since 30th July 2000) which aims to harmonize protection of biotechnological inventions including plant protection amongst the EU members. While in the U.S. and Australia plant varieties are patentable, patenting of varieties per se is not feasible in Europe. However, a plant which is characterized by a particular gene is patentable as it is not included in the definition of a plant variety. In Europe, transgenic plants are patentable as long as they are not restricted to a specific variety but represent a broader plant grouping. Furthermore, the European directive considers plant cells to microbiological products and therefore patentable (Patent Lens 2013).

Since genetic modification of crop plants came up, plant breeding companies are increasingly trying to protect their inventions by claiming patents on plant material and production techniques, leading to disagreements between farmers, companies and public. One of the major refutations of the opponent site is that genetic material generally cannot be invented and is thereby not patentable (Richter 2012). One of the main issues discussed in context with patents on plants is that patented varieties cannot be used in breeding programmes to create new varieties. While PVP only protects a variety in the way that only the breeder has the permission to reproduce and market the variety he has invented, patents prohibit any use of protected material. For this reason, there is the strong apprehension that patents on plants will drastically reduce genetic diversity.

Nowadays, patent offices are inundated with applications. “The US Patent and Trademark Office” (USPTO) alone reports a backlog of 1.2 million pending applications in 2010 (Parisi et al. 2013). According to the EPO’s (European Patent Office) Enlarged Board of Appeal (EBA), plant varieties produced by classical breeding methods using natural sexual crossings cannot be patented. However, in case of direct modification and introduction of particular genes, specific techniques and their products fall under the patent legislation (Blakeney 2012). In 2010, the ETC group, a non-governmental organization that “works to address the socioeconomic and ecological issues surrounding new technologies that could have an impact on the world’s poorest and most vulnerable people” (www.etcgroup.org) identified 262 patent families and 1663 patent documents for so-called “climate-ready” genetically engineered crops. Only 9 % of the patent families accounted for the ownership of the public sector, whereas 91 % where hold by the private sector. Three companies, namely DuPont, BASF and Monsanto accounted for 66 % of the total, underlining the level of concentration on the market for GM techniques (Blakeney 2012).

Regarding the average annual crop yield increase and the diversity of germplam in the last two decades, the introduction of strict intellectual property (IP) instruments (patents) and innovation through IP revenue streams has not compensated for the decrease in research funding (Heinemann et al. 2013). There is a rising concern that the patents amassed by the biotechnology companies will hinder innovation (Cukier 2006). Biological technologies are interdependent technologies requiring multiple key components to function, and denial of access to any component prevents the use of the technology. Additionally, the numerous patents could create a confusing situation, whereby the granting of so many property rights could lead to the underuse of innovations. Based on these critics, open-source practices are proposed for biotechnology, oriented on the open-source movement in information technology. One example is the BIOS (Biological Innovation for Open Society) initiative (BIOS 2013).

5.5. Conclusions

Scientific plant breeding approaches for any crop includes three basic steps:

- Creation of a new initial genetic variation;
- Selection of suitable crossing parents for creating new varieties;
- Testing, maintenance and reproduction of a variety.

Table 28 gives an overview in which breeding step the assessed breeding technologies are applied. Depending on the type of propagation of the crop, different breeding methodologies have to be applied. These formerly invented techniques are nowadays often referred to “conventional”, “traditional” or “classical” plant breeding. *Conventional breeding* covers all three basic steps for a crop breeding program and can therefore not be considered as a special tool or technique. Especially with the invention of hybrid breeding, stunning yield increases for several crop plants like maize, rice, rapeseed or rye were achieved. The current status of the particular techniques and their importance for research or practical approaches is summarized in table 29.

After the sexual crossing of two promising parental plants in conventional breeding, the genetic diverse progeny is phenotypically screened in testing fields. The most promising individuals are then selected and re-sown in the next breeding steps. A repetition of many cycles results in a homogeneous plant population that represents the new variety. The last breeding step deals with reproduction and maintenance of the new plant variety. Despite the great achievements by using classical approaches, there are some limitations of the methodologies in every basic breeding step.

For the *production of a new variety (first step of the breeding process)*, it is vital to create an initial genetic variation in order to produce plants with new favourable and interesting characteristics. Conventional breeding approaches are limited to the natural sexual compatibility of parental plants. However, there is often a lack of genetic resources for several traits of some crops. Wider related or even unrelated species often show favourable traits which would be interesting to introduce in new varieties, but cannot be combined via sexual crossing due to natural crossing barriers. For this reason, different techniques have been invented to either enable crossings of unrelated species or to enhance genetic variation using artificially induced mutations.

Table 28: Breeding technologies and their relevance for the three main breeding steps

Breeding technology	Induction of genetic variation	Selection of favourable genotypes	Testing, maintenance and reproduction
Conventional breeding			
- Breeding line varieties	+	+	+
- Breeding open-pollinated varieties	+	+	+
- Breeding clonal varieties	+	+	+
- Hybrid breeding	+	+	+
Mutation breeding			
- Use of physical mutagens	+	-	-
- Use of chemical mutagens	+	-	-
Tissue culture methods			
- Embryo rescue method	+	-	-
- Protoplast fusion	+	-	-
- Double haploids	+	-	-
- Micropropagation	(+)	-	+
Marker-assisted breeding			
- Molecular markers[1]	-	+	+
- QTL mapping	-	+	-
- SMART breeding	-	+	(+)
Breeding with genetic modification			
- Transgene approach	+	-	-
- Cisgene approach	+	-	-
- Novel GM techniques	+	-	-
Organic breeding	+	+	+
Participatory plant breeding	+	+	+

Legend: + high relevance; (+) restricted relevance, - no relevance
Note: [a] Molecular markers are also used to test the genetic purity of a variety
Source: Own assessment

An important technique that came up in this context is called "*mutation breeding*" or "mutagenesis". Plants are chemically or physically treated with mutagens that initiate random mutations throughout the genome and thereby create new genetic variations that can be of interest. Nowadays, there are over 2,300 registered plant varieties created by mutation breeding approaches covering different important crops, such as cereals, fruits, ornamental plants or roots and tubers. Especially countries with lower capital and technological options, such as countries in Africa or parts of Asia use this technique to a wide extent because it is well established and relatively cheap. Mutation breeding still plays an important role in crop improvement, especially in combination with new improved techniques. One very promising new technique is the TILLING approach that enables high-throughput screenings for wanted mutations from mutagenesis.

To enable crossings of plants that are naturally not combinable, different *tissue culture techniques* have been invented, such as the "embryo rescue method" or "protoplast fusion". In this methods, plants (and thereby their genomes) are combined on the cell level and afterwards artificially grown to fertile plants in special culture media which contains different plant hormones that stimulate plant growth. Using these techniques, many achievements could be made in the past. Several recent examples of the successful production of new improved rice varieties in West Africa and Asia using these techniques underline their importance for crop improvement.

Another approach to enhance genetic variation and to accelerate the process of combining favourable traits from related and unrelated species is *genetic modification* of crop plants. The principle is to directly transfer genes of interests from one organism to the plant genome. Up to now, there are numerous plant varieties produced by genetic modification (called GM crops). Maize, soybean, cotton and rapeseed are the relevant GM crops cultivated in agriculture. The key growing areas of GM crops are in North- and South America, China and India. In the EU, GM crops play a minor role, with Spain being the major GM maize growing country. The debate about the benefits and risks of GM crops is highly controversial. While some scientists see high potential in GM technology for distinct yield increases, there are numerous opponents stating social, environmental and health risks.

Until now it is relatively difficult to make a clear and general assessment of the performance of GM crops in comparison to conventionally bred varieties. There are studies that give evidence for distinct yield increase and rising benefits for farmers by using GM seeds. Other studies document that on the bottom line farmers did not achieve additional receipts using GM crops due to high seed costs which could not be compensated by higher yields or saved input. Others even state that farmers growing GM crops generated financial losses. Therefore the assessment of GM crop performance must be differentiated and aligned to the particular circumstance.

Table 29: **Breeding technologies and their relevance current status in research and practical application**

Breeding technology	Basic research	Applied research	Early adopters in practical breeding	Common approach in practical breeding
Conventional breeding				
- Breeding line varieties	-	-	-	+
- Breeding open-pollinated variet.	-	-	-	+
- Breeding clonal varieties	-	-	-	+
- Hybrid breeding	-	+	-	+
Mutation breeding				
- Use of physical mutagens	-	(+)	(+)	(+)
- Use of chemical mutagens	-	+	-	+
Tissue culture methods				
- Embryo rescue method	-	(+)	-	+
- Protoplast fusion	-	+	+	(+)
- Double haploids	-	-	-	+
- Micropropagation	-	+	+	(+)
Marker-assisted breeding				
- Molecular markers[1]	+	+	+	+
- QTL mapping	+	+	+	(+)
- SMART breeding[2]	+	+	+	(+)
Breeding with genetic modification				
- Transgene approach	+	+	+	(+)
- Cisgene approach	+	+	+	-
- Novel GM techniques	+	+	(+)	-
Organic breeding	-	-	+	(+)
Participatory plant breeding[3]	+	+	+	-

Legend: + high relevance; (+) restricted relevance, - no relevance

Notes: [1]Early molecular markers such as RFLP become less important for both research and practical approaches; new marker systems like SNP markers get more importance for research and practical breeding

[2] SMART breeding as genomic selection based on sequence information about genes of interest

[3] Mainly applied in developing countries with marginal acreage; extend of farmer participation can vary from low to full-involvement

Source: Own assessment

It is important to notice that the GM technology just represents one of different tools to create new initial variation. Conventional breeding methodologies remain indispensable for the further breeding steps. The considerable efforts in new plant biotechnology and genetic modification approaches could not have been achieved without the processing of several supporting techniques and research fields. Genome sequencing represents one of the most important and promising ones and makes it nowadays possible to sequence whole plant genomes at relatively low financial and labour costs. Connected with the bioinformatics sector and in cooperation with strongly enhanced phenotyping methods, DNA sequencing enables to explore gene functions and thereby represents a very promising and important field for plant breeding in the near future.

At the moment, new GM techniques are coming up, for example the "*cisgenesis*" and "*intragenesis*" technique. Both approaches follow the principle that the gene of interest origins from the same plant species or a closely related species. This means that in principle the gene transfer could also be arranged using classical breeding methods, but which would take much more time. The inventors and supporters of the techniques argue that because of the gene's origin these techniques should not be treated legally as a transgene approach. Opponents in turn argue that it is not only the origin of the gene which opposes risks, but also the applied transfer techniques. The EU GM regulation applies also for these new approaches.

"Breeding for organic farming" (organic breeding) and "participatory plant breeding" (PPB) represent special features in the list of breeding technologies. These are not special techniques in itself. They represent principles and/or organisation of breeding that can include listed specialised methodologies and procedures. *Organic breeding* supports the general principles of organic farming. Some of the newer breeding techniques, such as the GM or protoplast fusion technology are strictly prohibited for the production of organic seed. For other modern biotechnologies, it is not quite sure whether they truly fit in the ideals and principles of organic farming. While in the past organic farmers were mainly dependent on conventional breeding and classical bred varieties, the market for organic seeds is now growing due to a consistently growing demand for organic products. Especially for marginal regions, organic seed seem to have advantages towards conventional seeds because of their good adaptation to low-input farming systems. The widespread of organic seed is partly restricted because of the strict seed legislation which only accepts homogeneous seeds in the variety lists. Therefore, experts suggest to create a special category for organic varieties, landraces and traditional seeds in the seed registration regulations.

The *participatory plant breeding* approach came up in the 1980s and describes the collaboration between plant breeders and farmers in breeding programmes. Thereby, both farmers and breeding experts can benefit from cooperation: farmers know their production systems and the special requirements for plants grown in their area. Plant breeders have the technical and scientific breeding know-how. Whereas in technical highly developed countries with high-input agriculture systems participatory plant breeding did not have high importance for crop improvement, great successes in variety creation could be made in developing countries with marginal production regions. The fact that participatory plant breeding programmes are strongly supported and financed by several international public institutions indicates that the approach is assessed as sustainable for crop improvement.

In the *second major step* of any breeding process, *the best individuals of an initial variation must be identified and selected*. In classical approaches, plants with the best phenotypic performance for the trait of interest were selected in the testing fields. Although phenotypic selection still plays a very important role in plant breeding programmes and new improved techniques for precise phenotyping have been invented, the procedures have turned more and more to genotype-based methods, such as *marker-assisted selection (MAS)* or *SMART-breeding*. In principle, these techniques analyse the DNA composition of plants and identify individuals with the best genetic characteristics for particular traits. At the moment, MAS is widely applied in big breeding companies for different crop plants. The importance of the technique for practical breeding is underlined by the fact that there are approximately 2,900 patents related to MAS today, most of them hold by Pioneer, Monsanto and Syngenta.

According to the opinion of experts with practical breeding experience, MAS is mainly used for breeding aims like biotic resistances, classification of gene pools, quality assurance in seed production or abiotic stress resistances. While MAS deals with markers that represent unknown and random DNA parts in plan genomes, SMART-breeding follows the principle to select individuals on the basis of the presence or absence of special genes (or gene conformations) of interest whose sequences and protein expression effects have been identified.

Gene-based selection methods gain more and more importance as there is rapid progress in the gene sequencing and identification sector. Although there are early adopters, SMART-breeding is still in the development stage but with remarkable research efforts being made. Gene-based selection methods are assumed to allow a much more precise and effective selection in breeding programs and will increase the accuracy and success of breeding, especially in combination with improved modern phenotyping methods.

In the *last breeding step, the maintenance and reproduction step of a variety*, there are also classical and novel approaches available. In traditional approaches, the seeds of new varieties are harvested, stored and re-sown by the breeders every year in order to provide seeds for commercialisation. For clonal propagated crops, like potato, new techniques have been invented, like “micropropagation”, a tissue culture based technique. In this procedure, small plant material parts of elite varieties are cultivated on special medium, thereby producing a multiplicity of identical clones. The major advantage of this technique is that it uses meristematic cells of the donor plants that are not infected by viruses which means that the produced planting material is disease-free. This strongly contributes to food safety. To check the purity of a variety it is nowadays a common approach to use molecular markers (like in MAS).

Table 30 presents information about how applicable the different plant breeding technologies are for the most important crop plants and to which extend there are deployed currently. The information was taken from numerous scientific reports and articles which describe the applicability of the different techniques for different crops.

Conventional breeding methods are well established for all different kinds of crop plants and, as mentioned above, still very important for practical plant breeding up to now. Depending on the type of propagation of the particular crop plant the relevant method is applied. It is important to mention that for some crops, like maize, pure-line breeding methods are only relevant as a pre-step of hybrid breeding programs to create inbred lines. Hybrid breeding itself is not relevant for all crops. For example, the hybrid breeding method could not be established for wheat yet and is still in the development phase.

Mutation breeding in general has led to many new varieties of numerous crop plants. The technique is well established and used all over the world. Mutagenesis with employment of physical mutagens like radiation is described as less effective than using chemical mutagens. However for some crops, like soybean or sunflower, there are registered varieties produced by physical mutagenesis. As natural mutations occur very infrequently, mutagenesis is rated as a powerful tool to enhance genetic variation by several researchers.

Tissue culture based methods have become an established and widely used tool for plant breeding worldwide. There are reports of the successful application of all discussed techniques for nearly all crop plants. Techniques like micropropagation require both technical infrastructure and know-how which limits their application in parts of the world. However, with the technological achievements being made, costs of the approach may shrink in the medium term making the techniques applicable in more parts of the world.

The idea of marker-assisted plant breeding came up in the late 1970s and represents a cornerstone for plant breeding as classical phenotypic selection was advanced by genotypic selection approaches. Although the principle seemed very promising, MAS always lacked behind expectations in the past. This was due to several technical difficulties. Until now, MAS could be well-established as a widely used technique in both research and practical approaches. There are numerous reports and studies describing MAS approaches for all important crop plants. According to expert opinions of practical breeders, MAS is at the moment predominantly used in hybrid breeding, especially for maize, sugar beets, canola and hybrid rye. Main breeding aims associated with MAS are biotic resistances, classification of gene pools, quality assurance in seed production or abiotic stress resistances.

Table 30: Importance of the breeding technologies for important crop plants

Breeding technology	Cereals					Oilcrops			Roots and tubers		Sugar crops
	Maize	**Rice**	**Wheat**	**Barley**	**Sorghum**	**Soybean**	**Sunflower**	**Rapeseed**	**Potato**	**Cassava**	**Sugar beet**
Conventional breeding											
- Breeding line varieties	+*	+	+	+	+	+	+	+*	+*	(+)	+*
- Breeding open-pollinated varieties	(+)	-	-	-	-	-	-	+	(+)	(+)	+
- Breeding clonal varieties	-	-	-	-	-	-	-	-	+	+	-
- Hybrid breeding	+	(+)	(+)	(+)	+	(+)		+	+	(+)	+
Mutation breeding											
- Use of physical mutagens	(+)	(+)	(+)	(+)	(+)	+	+	(+)	+	+	(+)
- Use of chemical mutagens	+	+	+	+	(+)	+	+	+	+	+	+

Continuation Table 30: Importance of the breeding technologies for important crop plants

Breeding technology	Cereals					Oilcrops			Roots and tubers		Sugar crops
	Maize	**Rice**	**Wheat**	**Barley**	**Sorghum**	**Soybean**	**Sunflower**	**Rapeseed**	**Potato**	**Cassava**	**Sugar beet**
Tissue culture methods											
- Embryo rescue method	+	+	+	+	(+)	+	+	+	+		+
- Protoplast fusion	+	+	+	+	(+)	+	+	+	+	(+)	+
- Double haploids	+	+	+	+	(+)	+	+	+	+	-	+
- Micropropagation	-	-	-	-	-	-	-	-	+	+	-
Marker-assisted breeding											
- Molecular markers	+	+	+	+	+	+	+	+	+	(+)	+
- QTL mapping	+	+	+	+	+	+	+	+	+	(+)	+
- SMART breeding	+	(+)	+	+	(+)	(+)	(+)	(+)	(+)		(+)

Continuation Table 30: Importance of the breeding technologies for important crop plants

Breeding technology	**Cereals**					**Oilcrops**			**Roots and tubers**		**Sugar crops**
	Maize	**Rice**	**Wheat**	**Barley**	**Sorghum**	**Soybean**	**Sunflower**	**Rapeseed**	**Potato**	**Cassava**	**Sugar beet**
Breeding with genetic modification											
- Transgene approach	+	+	(+)	(+)	(+)	+	+	+	+	(+)	+
- Cisgene approach	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	?	(+)
- Novel GM techniques	(+)	(+)	(+)	(+)	?	(+)	(+)	(+)	(+)	?	(+)
Organic breeding	?	(+)	(+)	?	?	(+)		?	(+)	?	(+)
Participatory plant breeding	+	+	+	+	+	+	(+)	?	+	+	?

Legend: +high practical relevance; (+) restricted relevance, in research/developing stage; - no practical relevance; ?information not available

Note: * Line breeding methods mainly used to create high homozygous inbred lines for further hybrid breeding steps

Source: Own Assessment

Genetic modification of crop plants came up in the 1980s and is now established as an applicable technique for plant breeding, despite the fact that there are heated debates and many concerns about the application of this method. Globally, classical transgenic plants still dominate the GM crop market with herbicide and insect tolerance being the most important traits. However, genetic modification approaches are also used for other crops like rice or potato but with a lower importance. Also orphan crops like cassava are subject to GM research and there are already early adopters being tested. The research field "genetic modification" is globally constantly growing with several new techniques being investigated. However, the achievements that are being made in the research sector are not comparable with the practical application and marketability of new GM crops due to high durations for development and licence. In the EU, the legal frameworks are particular strict in comparison to other parts of the world. Every release of GMO to the environment is subject to authorisation covering both, commercial growing and outdoor tests. The number of GMO releases in the EU has constantly declined for several years, especially because of the heated moral and ethical debate being held in public and the low acceptance of GM products.

Organic breeding is more and more attractive as there is a constant increase of the organic sector. Until now, the situation of organic breeding in the EU is very heterogeneous and there is only a fractional amount of organic varieties in comparison to conventional ones. This is mainly due to insufficient financial means as breeding companies had no financial incentives due to a much lower demand for organic seeds compared to conventional. Germany is one of the EU Member States with a more advanced organic breeding system with a total of approximately ten cereal and 50 vegetable varieties registered in the national variety list. Because of increasing demands for organically produced food, it might reasonably be assumed that organic breeding will be enlarged and more varieties of other important crop species will be generated.

Participatory plant breeding mainly plays a role in developing countries with low-input agricultural systems and marginal production areas. Crops that are grown in these parts of the world like maize, rice or cassava are therefore mainly subject to PPB. However, progress of PPB programs has been faster for cereals than for other crops like roots and tubers. Especially self-pollinated species represent ideal candidates for PPB as selection and seed production for autogamous species can be conducted by farmers with lower efforts compared to open-pollinated, allogamous species.

6. REDUCING CROP LOSSES

6.1. Introduction

There are three types of discourses on food waste:

> estimating crop/food losses for better storage, marketing and delivery planning;
> highlighting the scale of food waste in relation to global malnutrition (moral and economic perspective); and
> proposing technical solutions in order to control food losses and hence, to increase food supply.

The latter is the most relevant to this study[39], while the publications on the two former provide important information on the situation.

Parfitt et al. (2010) distinguishes between food losses and food wastes, arguing that the former relates to early stages of the food supply chain (FSC) and refers to a system which needs investment in infrastructure[40]. In contrast, the term food waste is applied to later stages of the FSC, and generally relates to behaviour of food suppliers and consumers. This study concentrates on harvest and post-harvest crop losses before the raw material reaches processing. In the analyses are included losses which occur in the first four stages of the FSC as described in table 31.

Table 31: The scope and the structure of crop losses in this report

	Stage of the FSC	Examples of food loss characteristics
1	Harvesting—handling at harvest	Edible crops left in field, ploughed into soil, eaten by birds, rodents; Timing of harvest not optimal: loss in food quality; Crop damaged during harvesting/poor harvesting technique; Out-grades at farm to improve quality of produce
2	Threshing/shelling/chaff separation/ cleaning/ washing	Loss through poor technique
3	Drying/curing/cooling, transport and distribution	Poor transport infrastructure; Loss owing to spoiling/bruising
4	Storage	Pests, disease, spillage, contamination, natural drying out of food

Source: Based on Parfitt et al. (2010)

The last two stages (3 and 4) cannot always be clearly separated from primary processing and so do the losses.

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[39] Extended description of the topic reducing food losses in Annex E.

[40] "Investment in infrastructure" is understood in broader terms as investment in knowledge, technology, and transport and market infrastructures.

Reduction of food losses is within the mandate of the Food and Agriculture Organization of the United Nations (FAO). In 1974, the first World Food Conference (WFC) identified reduction of post-harvest losses as one of the actions which might significantly contribute to the reduction of world hunger. At this time, post-harvest losses were estimated at 15%, and the proposal settled at the WFC was to reduce them by half by 1985 (Parfitt et al. 2010). Initially, the main focus of the initiated "Special Action Programme for Prevention of Food Losses" was only on reducing losses of durable grain; later (in the 1990s), the scope of work had been broadened to cover roots and tubers, and fresh fruits and vegetables (FFVs).

However, the lack of adoption of effective measures led to no progress in reduction of post-harvest losses. The poor performance of the Special Action Programme can be accounted to the purely technical perception of the food losses problem. Instead, a more holistic approach is needed (Grolleaud 2002). Following this understanding, this chapter will not only identify gaps in technology and marketing infrastructure, but will also discuss organizational and institutional imperfections which prevent transfer of knowledge and investment in reducing crop losses effectively anywhere in the world.

Table 32: Product characteristics relevant to food supply chains and food losses

Categories of crops	*roots and tubers*	
	non-perishable (grains)	*perishable food crops (FFV)*
Harvest	seasonal	seasonal, but possibility of permanent or semi-permanent production
Preliminary treatment	threshing, drying (if needed), cleaning	drying for long term storage, washing
Fruit	small (below 1 g)	large (5 g - 5 kg)
Product moisture	low	high (50-80%)
Respiratory activity of stored products	low	high, very high
Tissue	hard, good protection	soft, highly vulnerable
Storage	long term (due to seasonality), good natural disposition	rather short term
Losses during storage	mainly from exogenous factors	both endogenous (respiration, transpiration, germination, etc.) and exogenous factors
Direct consumption	rare (need processing)	products for direct consumption

Note: Exogenous factors: pests, insects, rodents, stealing, etc.
Source: Based on Parfitt et al. (2010)

The focus of this study is on three categories of crops:

- grains (cereals and oilseeds),
- roots and tubers and
- fresh fruits and vegetables (FFV).

They differ in a number of characteristics (Table 32) of which the degree of perishability is one of the most important from the postharvest losses point of view. On one pole there are grains, on the other pole highly perishable fresh fruits and vegetables, root and tuber crops are in-between. The food supply chains, which include post-harvest technologies and marketing organization and infrastructure, are to large extent determined by product characteristics associated with perishability.

Both quantitative and qualitative food losses are considered in the literature. However, not all weight losses are necessarily food losses. Weight decreases due to respiration and transpiration might be considered as natural, as long as they have no effect on the quality and the opportunity to sell crops. Similarly, the loos of weight due to drying cannot be regarded as food loss (Hensel 2009). Degradation in quality usually results in impossibility to market such crops. Quality criteria depend on the use of crops and societal/consumer concerns; they include physical and chemical properties, colour, shape, size, nutritional value or absence of microorganisms, toxins and other pollutants (Hensel 2009).

Many authors (e.g. Hensel 2009; Hodges et al. 2010; Parfitt et al. 2010) point out that the nature of food losses and food waste depends on the stage of the development of FSC. Basic characteristics of FSC (without their further differentiation by the above mentioned product groups) are summarized in table 33. In general, the transition of FSCs goes from traditional semi-subsistence system toward highly integrated global food supply system.

Parfitt et al. 2010 distinguishes three main global drivers of the development of FSC: urbanisation and declining share of the agriculture in GDP, dietary transition and increasing globalization of trade. While dietary transition in developing/transitional countries results from urbanization (change of live style) and growing income, ageing of population is an important factor in developed countries. Hodges et al. 2010 describes that main food losses are due to spillage and biological spoilage in the first stages of the FSCs in developing countries; in contrast, the critical factor for food losses/wastes is in developed counties the growing intolerance of cosmetic defects or deviations from substandard food traits. Table 33 can be interpreted in the way that FSC chains in the developed countries are already results of the mentioned three global trends, while the other two FSC are at the early and progressed transition due to these drivers. But it can be expected that the different development stages of food supply chains will coexist over a longer time at the global level.

Table 33: Characterisation of the development stages of food supply chains (FSCs)

Class of countries	*Developing countries*	*Transitional countries (e.g. BRIC)*	*Developed countries*
State of economic development	*Low- income*	*Low- and - middle income*	*Middle and high income*
Type of growers	Smallholders, semi-subsistence farms	Dual farm structure, semi-subsistence farms and larger commercial farms	Medium and larger farms and large commercial farms
Harvesting technology	Traditional, often manual or simple mechanisation	Mechanised harvesting alongside the traditional systems	Harvesting highly mechanised
Post-harvest infrastructure	*Traditional* threshing, drying, storing, simple mechanisation	*Intermediate*, i.e. a mixture of sophisticated and traditional technologies	*Sophisticated* technologies, cold chains
Marketing system	Local markets	Local, urban and increasingly export markets	Centralised (supermarkets), export orientation
Level of vertical integration	Poor integration, many intermediaries supplying urban markets	Vertical coordination, less intermediaries	High vertical integration, even supranational
Quality	Variable quality, no requirements on standards	Variable quality, standards for export markets	Quality and safety standards central to the FSC

Source: Based on Parfitt et al. (2010)

6.2. Overview of harvest and post-harvest crop losses

Most authors agree on the difficulty and rather low reliability of the estimates of post-harvest losses. Measuring what has been lost implies that it is known what was there at the outset and this is usually not the case (Hoddges et al. 2010). Basically, two main approaches are adopted to estimate post-harvest losses: either to actually measure what has been lost or to use questionnaires to collect subjective loss estimates from those who have experienced them. The problem is that this basic methodological information is lost throughout the citations and transcriptions. In addition, some authors (e.g. Gustavsson et al. 2011) add their own assumptions which are based on similarities with other production systems and regions. There are differences among authors (and thus figures) in terms of operations which have been included in post-harvest handling (Grolleaud 2002). As illustrated in table 33, the ranges of crop losses estimates can be really wide. The variance of estimates depends amongst others on applied methods (authors), year of the survey and other unreported parameters. As noted by Tyler (1982) “postharvest losses may be due to a variety of factors, the importance of which varies from commodity to commodity, from season to season, and to the enormous variety of circumstances under which commodities are grown, harvested, stored, processed and marketed.” It is therefore important not only to work with figures that are good estimates at the time and in the situation they are taken but to be aware that at other times and situations the figures will differ.

The purpose of estimating food losses is also important: if it is for calculations of food availability, all losses should be included; however, if the estimates should guide actions to combat food losses than they should include only avoidable losses. One has to understand that due to mechanical or biological processes (e.g. respiration) some post-harvest losses are unavoidable (Grolleaud 2002). Also social contexts might be important in determining what food loss is and what not (important when subjective judgments are surveyed).

Below, the assessments of post-harvest losses are presented by commodities or groups of commodities, macro regions[41], countries and by climatic and weather conditions. Macro regions refer primarily to various levels of the development of FSCs and their economic environment worldwide, nevertheless, when interpreting the figures one has to take into account also climatic differences.

The importance of harvest and post-harvest losses within the FSC and within overall food losses/wastes in different commodity chains is illustrated with figure 23. The percentage distribution of food losses is based on the extensive work of Gustavsson et al (2011). The advantage of Gustavsson’s study is that it provides “complete” geographical coverage (differentiated by marco regions). However, the authors do not hide that their estimates are based on various sources and sometimes on their own judgments. A certain level of consistency is guaranteed by using exclusively FAO data on food production and consumption and by assuring balance between production, use and losses at each stage of the FSCs.

There are substantial differences in harvest and post-harvest losses between developed (the three left columns in each graph) and developing and transitional countries. Particularly post-harvest losses are very low (6-14% of all food losses) for all three commodity groups in developed countries, while these might be the most important (up to 44% of all food losses) in less developed regions. This is without doubts due to better post-harvest technologies, particularly storage facilities. However, the temperature and humidity is also an important factor affecting post-harvest losses; these are particularly high for cereals, and root and tuber crops in Sub-Saharan Africa and South and Southeast Asia.

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[41] Groups of countries of similar climatic, geographical and socio-economic characteristics

Figure 23: The importance of harvest and post-harvest crop losses within FSC presented by commodity groups and macro regions

Commodity groups: Cereals: wheat, rice (milled), barley, maize, rye, oats, millet, sorghum, other cereals.

Roots and Tubers: potatoes, sweet potatoes, yams, cassava, other roots.

Fruit and Vegetables (including bananas): oranges and mandarins, lemons and limes, grapefruit, other citrus, bananas, plantains, apples (excl. cider), pineapples, dates, grapes (excl. wine), other fruit, tomatoes, onions, other vegetables.

Source: Based on Gustavsson et al. (2010)

However, this gives only a general overview, because global regions are not homogenous in terms of economic development and climate. Table 34 present estimates of harvest and post-harvest losses in individual countries (without developed countries). These estimates come from various authors, from various periods, using various methodologies. The figures are often presented as ranges, often very broad ranges. Especially highlighted are three of the BRIC countries which are transitional countries (with a transitional FSC). However, they do not differ from the rest of the countries in terms of reported harvest and post-harvest losses. At the bottom of the table, scarce estimates of harvest and post-harvest losses of the three former Soviet Union countries (CIS – the Commonwealth of Independent States) are reported. Also these do not differ from the other countries substantially.

Table 34: Harvest and post-harvest losses by countries and commodities

	Country	*Rice*	*Maize*	*Wheat*	*Sorghum*	*Pulses/ oilseeds*	*Roots and tubers*	*FFV*
Africa	*Egypt*	2.50%						
	Sudan	17%		6-19%	6-20%	4-27%		
	Nigeria		10-70%		0 - 40%	5%		50%
	Ghana		7-14%			7-45%	15-60%	10-50%
	Kenia		10-23%				10-20%	30-35%
	Uganda	11%	4-23%			30%		
	Tanzania		20-100%			18%		
Asia	*India*	6%	4-8%	2-5.2%	7.50%	4-5.7%		20-30%
	Pakistan	2-10%	2-7%	5-10%	7%	5-10%		
	Indonesia	6-17%	4%		4%	5%		25%
	Malaysia	17-25%						20%
	Philippins	9-34%						10-50%
	Sri Lanka	10-40%						20-40%
	Thailand	8-14%				10-30%		20-30%
	China	5-23%						10-35%
South America	*Brasil*	1-30%*	15-40%*	15-20%*		15-25%		8-10%
	Paraguay		25%			15%		17-30%
	Bolivia	16%						
	Mexico		10-25%					
	Venezuela		10-25%					
	Dom. Rep.	6,5%	9%					25%
CIS	Ukraine		14-32%*	14-32%*				
	Moldova							5-25%
	Kazakhstan		12-30%	12-30%		30%		

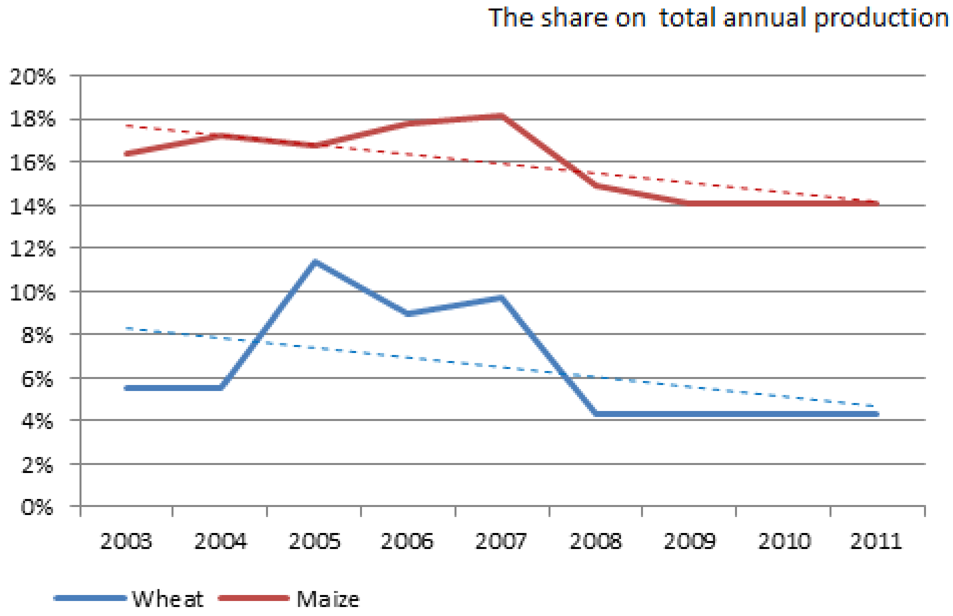
* likely improved substantialy since it was estimated

Source: Hensel (2009); Parfitt et al. (2010); Striewe (1998); Shpychak (1998); Maloney (2006); Satybaldin & Grigoruk (2002); Kader (2009)

A common observation is that upper ranges of post-harvest losses are pretty high for almost all grains and countries. Although grains are not perishable, substantial part of the high loss figures ought to be accounted to storing. As it will become apparent later, higher storage losses are associated with wet weather (climate), inappropriate post-harvest treatment and poor storage facilities.

Because of lack of consistency in food losses data, it is very difficult to assess the dynamics of post-harvest losses. The loss estimates for Ukraine are a good example. The estimates in table 34 come from the two surveys (Striewe 1998; Shpychak 1998) conducted in 1998. No later figures are available. However, in the meantime, the post-harvest sector got privatized and new (foreign direct) investment has reached the sector (Striewe 2011). It is very likely that storage losses dropped accordingly.

Figure 24: The development of post-harvest losses in East and Southern Africa



Source: APHLIS (2013)

The "African Postharvest Losses Information System" (APHLIS) addresses the need for a systematic survey of post-harvest losses – particularly for better forecast of food supply in Eastern and Southern Africa. The longest available time series was found for maize and wheat (Figure 24). In spite of a period of increased post-harvest losses (2005-2007 for wheat and 2006-2007 for maize), both commodities exhibit a long term decline of losses (the down-sloping trend lines).

The Central Institute of Post-Harvest Engineering and Technology in India reported substantial declines of post-harvest losses by 25% for wheat, 50% for rice, 45% for maize and 40% for pulses between 2004 and 2010 (CIPHET(ICAR) 2010).

6.3. Options to reduce losses in the grain sector

Harvest and post-harvest treatment of grains include four steps:

- Cutting cereal plants (Harvesting)
- Threshing/shelling ,winnowing/cleaning (Separating grain from the ear)
- Drying (parboiling in the case of rice)
- Storing

Grain harvest and postharvest technologies vary across farming systems and regions. Two technological lines can be distinguished:

1. Modern, which uses combine harvester unifying the two first steps in one, and also fine cleaning and drying are usually integrated with storing. This set of technologies is largely mechanised and is demanding energy (electricity, fuel) for drying and handling. Grain is stored in bulks in metal or concrete silos. Scale of operations is large; farmers often cooperate horizontally and are fairly integrated with large grain merchants or processors (milling industry).
2. Traditional, in which all four steps are conducted separately. The share of manual work is high. In many parts of the world, manual harvesting, threshing, winnowing, open sun drying prevail on small farms. Semi-subsistence farmers store their grain in their farmhouse in sacks or bins. The food chain includes several rather small intermediaries storing crop temporarily before transported to mills or large grain elevators (public or private). For better handling, grain is transported and stored in bags.

In practice, there are various transitional forms. Often, the government or a governmental organisation is involved in grain logistic and storing for strategic food security reasons.

Despite the improvements in agro-technology, particularly improvements of the effectiveness and availability of pesticides, harvested grain will still be threatened by biodegradation spoilage mainly due to moulds (e.g. Aspergillus, Penicillium and Fusarium). This will be discussed in a special paragraph on moulds and mycotoxins (Chapter 6.6).

Generally, the main R&D stream in postharvest technology for grains aims at reducing crop losses and labour input. Technologies are capital intensive, and in their scale usually suitable for well integrated cereal food chains with large farmers or farmers' cooperatives and big intermediaries. If managed well, the modern system produces very limited grain losses. The main losses due to spillage or mechanical damage of kernels can be attributed to handling and poor maintenance of combine harvesters, transport vehicles, transport belts or fanes. Regular upgrading and good maintenance of machinery and equipment will assure low losses of this type.

In contrast, high harvest and postharvest losses are immanent to poor small semi-subsistent farmers and small intermediaries. These small farmers rely on traditional technologies. Ranges of crop losses (as compiled from various sources, Table 35) are broad; the loss might be high at each postharvest treatment step.

Table 35: The range of grain losses at each postharvest treatment step in developing countries

Threshing	Drying	Parboiling (only rice)	On farm storage	Handling and transport	Central storage
5-13%	1-5%	1-2%	1-15%	3-10%	1-6%

Source: Compilation from various authors: Hensel (2009); Hodges et al. (2010); Parfitt et al. (2010); Rembold et al. (2011)

The traditional threshing of cereals includes a number of methods (FAO 1994; IRRI 2013): by hand, by being trodden underfoot (by humans or animals) or by using a vehicle circulating over cereal bunches as these are thrown on to the threshing area. The associated productivity gains of mechanisation are apparent (manual threshing with 10-30 kg per hour, comparing to 300-2000 kg per hour of the modern thresher). The threshing rate of the modern thresher is higher than 99%, while 1-4% of grains might remain in ears and spilled when manual and by foot method is applied. The traditional cleaning method is winnowing, which uses the wind to remove light elements from the grain.

The traditional ways of threshing and winnowing are gradually replaced by mechanisation: Great contributions comes from international research centres like International Rice Research Institute (IRRI), International Maize and Wheat Improvement Center (CIMMYT), French CIRAD etc. to the development of threshing and cleaning engine powered equipment suitable for small farmers in developing countries. Easy handling and versatility (maize, millet, sorghum, etc.) are necessary preconditions for a successful adoption of these mechanisations. The great efficiency of the mechanisation attracts interest of farmers even in countries where labour is cheap and abundant (Ethiopian ATA 2013). In many cases, saving time is the main motivation for adopting mechanised threshing and cleaning on small farms where these operations are usually done by the farmer or his spouse themselves. Another motivation (particularly for using a grain cleaning machine) is increasing requirement of quality standard when grain is sold on the market (FAO 1994).

Even if chosen the small one, the modern threshing and cleaning equipment will often greatly exceed the needs of individual farmers in developing countries. Unless the equipment is shared among farmers (either in a cooperative way or commercial way), the spread of the technology is limited; particularly when taking into account cost of \$1000-\$2000. Sharing the threshing equipment requires planning harvest and substantial level of social capital.

The efficiency, quality and level of losses vary greatly due to various input and operational factors like cultivars (some might be difficult for traditional threshing/shelling, FAO, 1994), humidity of input crop which might vary during the day (Alizadeh, Khodabakhshipour 2010; Asgha et al. 2004), the selection of a beater and the speed of the thresher drum (Peksen et al. 2013). This implies that progress in threshing technology must include beside new machinery also rising knowledge of those who operate this machinery how to control the threshing process.

Moisture content is a critical factor for storing, since high moisture content encourages fungal and insect problems, respiration and germination. If weather is wet during harvest or the crop is harvested too early, the grain must be dried. The simplest traditional method is sunshine thin-layer drying on an open platform or a simple maize crib. On the other pole is a continuous-flow (fuel heated) dryer, usually integrated within the large (central) grain storage. The losses are usually low regardless which system is used; grain is lost usually due to spillage. Thus the important thing is the choice of effective drying equipment with an effective moisture control system as a precondition of low storage losses.

Both the natural (based on direct sunlight or natural air movement) and artificial (using powered movement of heated air) drying systems must be designed to have sufficient capacity to be able to keep pace with the harvest rate, i.e. that it does not hold up the harvest (FAO 1994). The choice depends also on capital and running costs of the system.

There are some simple methods for assessing if the moisture content has dropped to its required level, which perform relatively well (e.g. the salt-jar method, FAO 1994). Nowadays, there is a good offer of handheld grain moisture meters on the market; the price ranges from \$150 to \$800 (Professional Equipment 2013).

Two types of grain storing can be distinguished, by their location on farm or outside the farm. Farmers store the crop on their farms for own consumption, including household consumption and animal feeding. Additionally, grain is often kept on farms awaiting a better price later.

The modern grain storage technology uses metal or concrete silos which can be perfectly sealed as well as ventilated if needed. A drying unit is usually part of the storage system. Grain is stored in bulks and the loading and unloading processes are fully mechanised. Moisture and temperature inside the silos is monitored continuously and the system is designed in the way that corrective actions can be taken if needed. However, such technology is investment intensive. The storage capacity is high (although smaller metal bins are also available, see later). Therefore, mostly large farmers invest in such a technology. Huge central grain elevators are usually built by large merchants, processors and governmental bodies. In spite of the high investment costs, the cost of grain storage in silos (including drying) per tonne per year is about US$7 - US$14 i.e. about 2-4% of the current wheat price[42] (ISU 2013).

In South America, North America, Ukraine or Russia large scale farmers use large hermetic plastic bags (silo-bags) for storing grain. These silo-bags can hold approximately 200 tonnes of wheat and with the available handling equipment it is quite simple to load and unload them. While silo bags provide easy and cheap on farm grain storage (up to 12 months, Bartosik et al. 2008), there might be a problem with the disposal of used bags (Holmes, Springman 2009).

Medium size farmers, groups of farmers (in a village) or smaller intermediaries tend to use warehouses where grain is stored in sacks or bulks. Small farmers in developing countries use traditional storage systems and their improvements. Quite a rich list of storage facilities for small farmers in developing countries is presented in FAO (1994) or in Hayma (2003). The list of more traditional technologies include jute sacks, clay pots, maize cob crib, earthen silo, Burkina silo made of bricks or metal drums, usually disused water or oil tanks. The problem of the traditional storage technologies is that they provide rather poor protection against insects, rodents and water. Improvements include plastic sacks which can be hermetic sealed – a small version of the above mentioned silo-bags. Another example of an improved technology is the Indian Pusa bin, a double-walled silo with a separating layer of plastic sheet between the walls. The plastic protects against moisture and keeps air from entering the stored product, provided the openings can be tightly closed. It gives good protection against insects and rodents, if the bottom part is made of fired bricks or concrete. The rest of walls can be made of mud blocks (Hayma 2003). In spite of being considered as expensive, small metal silos were successfully introduces in many places either at village or farm household levels (Anon 1982; EGSPI (2008-2011), EGSP-II (2012-2016) projects).

6.4. Options to reduce losses in the root and tuber sector

Harvest and post-harvest treatment of roots and tubers (cassava/manioc, yam, sweet potatoes[43], potatoes) include four steps

> Harvesting roots and tubers from the soil
> Sorting and cleaning
> Curing (healing wounds)
> Storing

Like for cereals, there are traditional and modern technologies of roots and tubers postharvest procedures. Similarly to cereals, roots and tubers are important crop for the subsistence of rural population, but they are also still more demanded by and produced for urban areas and export. This represents an important factor of commercialisation of roots and tubers production. Commercialisation brings with it pressure on productivity and efficiency of crop cultivation as well as postharvest procedures, and thus on modernisation of the production and distribution processes.

Harvest and postharvest losses of roots and tubers can be classified as physiological (caused by the effect of environmental conditions, table 36), pathological (cause by the attack of pathogens, e.g. fungi, bacteria, insects etc.) and endogenous (caused by endogenous processes like respiration, transpiration and sprouting). Of the four mentioned crops, cassava is very difficult to store and therefore is processed quickly after harvest.

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[42] In the past before price soaring, it was about 5-10% of the price).

[43] Yam (Dioscorea sp.), Sweet potato (*Ipomoea batatas)- which is sometimes called also yam.*

Reducing harvest and postharvest losses is essential for improving food security of small (semi)subsistence farmers and poor rural households for which potatoes, sweet potatoes, yams and cassavas are staple food as well as for improving efficiency of the distribution system delivering food to urban population.

Table 36: Physiological (environmental) factors affecting postharvest of root and tuber crops

Factors	Period	Crop	Effect on postharvest
Heavy rains – asphyxiation	Pre-harvest, harvest	Sweet potato	The crops decay shortly after harvest
Drought followed by intensive rains	Pre-harvest, harvest	Yam	Thin skin prone to cracks
Mechanical damage	Harvest, postharvest	All roots and tubers	Wounds prone to the attack of pathogens
Exposition to the sun	Harvest	Sweet potato	Scald, it can be site for postharvest decay
	Harvest, postharvest	Potato	Overheating, increasing the crop susceptibility to decay
Chilling injury	Postharvest	Sweet potato, yam	Susceptibility to decay
		Potato	Starch is converted in sugar

Source: Various sources referred in this chapter

Weather extremes, exposition to extreme temperatures (high, low) during pre- and postharvest and rough handling are main factors of physiological losses. They not only reduce the value of the crop due to damaged appearance, but temperature or mechanical injuries can be followed by invasions of pathogens leading in the decay of the attacked crop in the storage. Some weather effects can be hidden having tremendous impact on crop storage: for example heavy rains close to harvest that saturate soil for more than a few hours can cause sweet potato asphyxiation, i.e. an excessive carbon dioxide accumulation in tubers. Sweet potatoes that have been asphyxiated may appear healthy for several days or weeks, but if injury was severe, the roots will die and begin decomposing in storage (Edmunds et al. 2007).

The wound type and the level of damage have a big influence on the development of postharvest rots. Scuffs, splits and skin grazes, etc. are entry points for rots (Edmunds et al. 2007; Opara 2003; Meyhuay 2001). Uninjured and cured tubers do not develop postharvest rots (Jobling 2000). The damages are caused by harvesting instruments and handling as well as by insects, nematodes (yam) and rodents. Often, the effect of damages does not become evident until several weeks after harvest.

While bacterial rots lead to a rapid decay of tubers and roots, most moulds are also toxical; mycotoxins spread through the rood/tuber and even if the infected part is removed, the rest of the root/tuber is poisonous. Number of authors (e.g. Gnonlonfin et al. 2008) state that, particularly in tropical Africa, the presence of mycotoxins is high in yam and cassava roots as well as in dried chips.

With high temperature and after the natural dormancy period, tubers tend to sprout. With sprout growing, both respiration and moisture loss will increase rapidly, lowering the value of the crop.

Successful storage starts with high-quality roots/tubers. Traditional harvesting of roots and tubers is done by hand using diggers; simple mechanisation is used for potatoes, sweet potatoes, cassava and some smaller varieties of yam. Advanced mechanisation is used only for potatoes and sweet potatoes, usually, in order to reduce labour intensity in commercial farming systems. In contrast, yam and cassava harvests remain heavily labour intensive also in countries producing these crops for export[44] (Bokunga 1999; Opara 2003). The technical constraint to the mechanical harvest of yam and cassava rests in size and distribution of tubers and roots in the soil. The dominance of small-scale farms represents an institutional constraint to the spread of mechanisation in root and tuber production in many developing countries (Opara 2003).

During sorting, ground, stones, vegetal wastes, cut or rotten tubers/roots are separated. Sorting is achieved manually or with sorting machines. The second case offers advantages such as efficiency. Whichever method is chosen, contusions or bruising should be avoided.

Generally, use of water should be avoided before long term storage of tubers/roots, since it increases susceptibility to microbial infection and growth (Opara 2003; Edmunds et al. 2007). Potatoes can be washed before storage, provided that they are fairly dried afterwards (Jobling 2001).

Relatively clean tubers sold in the local market may not require any further cleaning. However, many urban and export markets require yams, sweet potatoes and potatoes to be washed. Yam should be washed by hand in clean water to remove any remaining dirt and to sanitize the tuber surface (NGMC 2013). Mechanical washing can be used for potatoes and sweet potatoes[45] if the produce quantity is large (Meyhuay 2001; Edmunds et al. 2007). Washed tubers/roots must be dried before packaging.

Because of tiny skin and fragility of the root or tuber crops, harvest damages are not fully avoidable, even if the harvest is done by hand. But roots and tubers exhibit self-ability of healing. Curing should be carried out as soon as possible after harvest. Regardless of which crop is to be cured, the roots and tubers must be kept at the right temperature to stimulate skin healing. Traditionally, yams are cured by drying the tubers in the sun for a few days. The optimum conditions for yam curing are 29°-32°C at 90-96% relative humidity for 4-8 days. Curing of potatoes is carried out by maintaining tubers at temperatures from 16°C to 21°C with 90% relative humidity during approximately 10 to 15 days (Meyhuay 2001). In general, good ventilation should be provided so that oxygen is supplied, and the air around the roots or tubers must be kept moist but without free moisture on the surface. To control humidity, humidification equipment (humidifiers) and measurement devices (psychrometer or electronic sensors) should be used. Modern facilities are also equipped with a powerful fan which is able to provide uniform conditions of temperature and humidity throughout the mass of roots/tubers.

In many developing countries, roots and tubers are stored and traded without a proper curing treatment. Often the uncured tubers are packed straight into poorly ventilated bags with damp soil still attached to the surface. Then crop is prone to decay and postharvest losses are very high.

Only sufficiently dried and clean crop should be put in the storage. Temperature and humidity must be controlled during storage: The optimum storage temperature for potatoes depends on their final use. It is recommended that fresh market potatoes are stored between 5 to 6^{o}C. Potatoes that are used for making chips are stored between 7 and 10^{o}C. Sweet potatoes and yam tubers are chilling sensitive. Sweet potatoes and yam should be stored at 13°C and between 12.5°C and 15°C respectively, with high relative humidity over 90%. A storage life of 13 and 6-10 months (respectively) can be expected under these conditions (Opara 2003; Edmunds et al. 2007).

Respiration of tubers produces heat which is to be conveyed away by ventilation. The forced ventilation (by a fan of sufficient capacity) is often needed to provide more effective heat transfer than can be achieved by natural ventilation. To safeguard the effective heat transfer, the crop should be stored in the

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[44] e.g. cassava in Thailand

[45] Clean water is a necessary precondition, some disinfection can be added.

way that forced air can reach each tuber. Thus, the type of ventilation and the storage structures (sacks, containers, barns or bulk storage) must be harmonised.

Higher temperature and long storage will lead to sprouting. Sprouting contributes to weight and quality losses as it was pointed out earlier. The use of sprouting inhibitors is recommended for long term storage. To avoid development of green spots[46] on potatoes dark storage is needed.

Traditional storage facilities for potatoes, sweet potatoes and yam (field piles, warehouses, yam barns or underground structures) often give little possibility for controlling temperature and humidity and usually provide poor protection against rodents and pests.

In contrast, the modern warehouses are usually air conditioned, refrigerated and well protected against insects and rodents. However, these are not affordable for small semi-subsistence farmers. Thus the surplus crop tends to be sold immediately after harvest. Nevertheless, there is still space for the improvement of the traditional technologies and the enhancement of knowledge and skill of small semi-subsistence farmers in order to save most of the harvest, thus reducing losses. It involves improvements of pre-harvest and harvest techniques, curing and rodents and insect protection of storage facilities with materials largely available to small farmers (Meyhuay 2001; Opara 2003). The use of simple evaporatively cooled structures (ECS) to lower temperatures inside a store has been tested. According to Fuglie (1999), average losses after three months of storage were by 60% lower comparing to traditional farmers' clamps. However, ECS involves some construction and maintenance costs and thus the acceptance of the technology by farmers depends on whether the benefits from lower losses and higher prices are sufficient to offset these costs.

So far the attempts to construct cassava storages have failed due to inability to control effectively temperature, humidity and the development of moulds (Bokanga 1999). Because of the perishability of cassava (and also their size), roots are chipped, dried and then stored. The first step in processing cassava roots in chips is to remove the peel. Peeling is usually done by hand using a knife, which is a slow and labour-intensive process, with about 25 kg per man-hour. Mechanical peelers and other attempts, including chemical ones have proved rather impractical so far (Bokunga 1999).

Traditional manual chipping of cassava roots is slow and produces irregular chips that take 3 to 7 days to dry. Mechanical chippers have the advantage of producing smaller and uniform chips that dry rapidly between 6 to 8 hours of exposure to the sun. When manually operated, the chippers have a capacity of about 60-70 kg/hr; but the engine powered ones can have a capacity of 1000kg/hr (Bokanga 1999).

6.5. Options to reduce losses in the Fresh Fruits and Vegetables sector

Although fruits and vegetables cannot be considered as staple food, they are, nevertheless, important sources of essential minerals and vitamins in the human diet. Some fruit and vegetable produce is immediately processed (canned, pickled, frozen)[47]; in this case there is very little space for postharvest losses. There are four main causes of postharvest losses in the area of fresh fruits and vegetables (FFV) (FAO 1989; Gross et al. 2004):

1. It is typical for fruits and vegetables that biological processes like ripening continue after harvest at relatively high speed. Thus crop spoils if it is not consumed immediately;
2. Mechanical damage during harvest , transport and handing, damaged crop might be more prone to pests (e.g. mould attack);
3. Bacterial and fungal infestation during the late vegetation period or harvest handling causing consequent spoilage. The propensity of some crops (e.g. strawberries or mango) to this type of spoilage is particularly high;
4. Storage linked damages (chilling or freezing injuries, too high CO_2 concentration, etc.)

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[46] Containing solanin which can end up being toxic

[47] Dried fruits are usually added to fresh produce.

Technologies to address the first three causes include: (a) appropriate chemical and biological protection of crops at field/orchard before harvesting; (b) timely harvest, using appropriate harvest methods based on manual picking-up, choosing appropriate and clean containers and the discipline of worker harvesting the crop; (c) cooling down the crop often together with controlling availability of oxygen in order to slow down ripening and other biological processes, (d) appropriate packaging and (e) careful, refrigerated and timely transport. Actually, these points (a) to (e) more or less represent stages in a sequential process of FFV production and distribution which is called cold chain. Failure at the preceding stage will almost inevitably cause losses in the following steps. During the process, high hygiene standards must be fulfilled.

Table 37: Storage parameters of selected fruits

	Pre-storage treatment		Storage			
	Pre-cooling	Curing	atmosph.	temper. C	relative humidity	period
Strawberries	forced air cooling, (1h after harvest)	-	MAP (10-30% CO2)	0	90-95%	7 days
Cherries	hydro- or forced air cooling		CA and MAP	-1 to 0	>95%	2-4 weeks
Apple	room cooling, forced-air cooling		RA	-1 to 4	90-95%	up to 4 months
			CA (ULO)	0-2	90-95%	up to 12 months
Oranges	room cooling, hydro- or forced-air cooling		RA	0-1	85-90%	12 weeks
				3-8	90-95%	
Mango	room cooling, forced-air cooling	to be kept at higher temperature for a day	RA	10-13	85-90%	up to 3 weeks
Banana	No		CA (2 -5% O_2 and 2 - 5% CO_2)	13.3-14.4	90-95%	4-6 weeks

Note: RA – Regular Atmosphere, CA – Controlled Atmosphere, ULO – Ultra Low Oxygen, MAP – Modified Atmosphere Packaging

Source: Gross et al. (2004)

In contrast, the fourth type of damage results from the effort to prolong the storage life of crops by applying the cold chain technology. It includes chilling and freezing injuries, CO_2 injuries, etc.

Table 38: Storage parameters of selected vegetables

	Pre-storage treatment		Storage			
	Pre-cooling	Washing	atmosph.	temper. C	relative humidity	period
Lettuce	vacuum cooling	-	RA	0	90-95%	3 weeks
Tomato	hydro- or forced air cooling		RA	>10	90-95%	2 weeks
			CA (1-3%O2)			6 weeks
Snap and long beans	hydro- or forced air cooling		RA (CA)	0	95-100%	3 weeks
Cauliflower			RA	0	95-100%	3 weeks
Cabbage			CA	0	98-100%	6 months
Bunched green onion	hydro-, forced air - or vacuum cooling		RA/CA	0	98-100%	4 weeks (8 if CA)
Dry onion	room or forced air cooling		RA	0	98-100%	up to 9 months
Carrot	Hydro-cooling	water with cholorine	RA	0-1	98-100%	6 months

Note: RA – Regular Atmosphere, CA – Controlled Atmosphere, ULO – Ultra Low Oxygen, MAP – Modified Atmosphere Packaging

Source: Gross et al. (2004)

It is obvious from table 37 and 38 that the cold chain technology includes many attributes which must be adjusted to individual crops, because various fruits and vegetables are differently sensitive to the parameters like relative humidity, temperature, atmosphere composition etc.. It holds not only between crops, but also it concerns crop varieties.

Produce is usually cooled to its storage temperature in special facilities designed to rapidly remove produce heat. Gross et al. (2004) present four (pre-)cooling technologies: (1) Forced-air cooling is the most widely adaptable method and is commonly used for many fruits and fruit-type vegetables; (2) Hydro-cooling uses water as the cooling medium and is less widely used than forced-air cooling because some products do not tolerate water contact, and it requires the use of water-resistant packaging; (3) Vacuum-cooling is usually applied to leafy vegetables that release water vapour rapidly allowing them to be quickly cooled; (4) Room cooling is accomplished by placing warm produce in a refrigerated room. Cooling times are long, at least 24 h. It is used for a few commodities, such as citrus or onion. The need or extent of pre-cooling can be significantly reduced if the crop is collected early morning, or if it stays in the open air overnight.

Transport cooling in refrigerated ships and containers is used for products in areas with no cooling infrastructure, such as bananas. Highway trailers have insufficient airflow to cool produce and should never be depended on for initial cooling. Package icing utilizes crushed ice to cool and maintain product temperature and is used for a very few commodities, mainly for those whose purchasers have a strong traditional demand for this method.

We can distinguish two modes of storage atmosphere: regular air/atmosphere (RA) and controlled atmosphere (CA). Controlled atmosphere storage involves reducing oxygen and increasing carbon dioxide in the air composition (O_2 from 21% to less than 8%, CO_2 from 0.03% to values ranging between

1% and 3%) in order to inhibit the ripening process. Atmospheric modification should be considered as a supplement to maintenance of optimum ranges of temperature and RH. Storage under 1-3% O_2 is referred to as Ultra Low Oxygen (ULO) storage. ULO is used for the long-term storage of apples, pears, blue berries and kiwis. In general, the lower the oxygen concentration, the longer the fruit can be stored. There is, however, a lower limit of the oxygen concentration. Dynamic controlled atmosphere storage allows going below 1% O_2 concentration being constantly adjusted on the basis of the fruit's respiratory activity.

Similar principle is applied in the Modified Atmosphere Packaging (MAP), which reduces transmission of gasses between the inner and outer atmosphere. In the effect, the concentration of O_2 decreases while the concentration of CO_2 increases which in turn limits ripening. MAP is applied to leaf vegetables like lettuce or spinach (Danish Technological Institute 2008).

Alternatively, chemicals can be used to delay ripening (My Agriculture Information Bank, 2011): for example Kinins and Kinetins delay chlorophyll degradation of leafy vegetables; Gibberellins (GA) markedly retards ripening of tomatoes, banana, kaki fruits, lemons and navel oranges. Growth retardants might inhibit storage sprouting of onions, turnips, carrot and potatoes. A productive method of inhibiting fruit ripening is to inhibit ethylene perception by gassing the molecules with 1-ethylcyclopropene (1-MCP)[48].

Fungal spoilage during postharvest and storage represents serious economic losses to producers. Thus, only sound, intact fruits and vegetables should be stored or used for processed fruit products. Gentle and sanitary handling of the fruit during harvest and in storage and processing facilities is essential for reducing fungal decay and mycotoxin production in fruits. Generally, the refrigerated storage and controlled atmosphere reduce development of fungi and mycotoxin production. Additional protection against fungi and mycotoxins includes postharvest fungicidal treatment, ozonification and washing fruits and vegetables in water with hypochlorite or diluted ozone.

Controlled atmosphere with very high CO_2 concentrations (10-60%) can have a direct or indirect effect on postharvest pathogens (bacteria and mould) and consequently on crop decay. Since such high concentrations of CO_2 and low concentrations of O_2 can damage the crop, sanitary atmosphere alternations can be done for only a short period (Gross et al. 2004).

Exceeding the range of safe values of temperature and gas concentrations, the stored crop will be injured (chilling, freezing injury, high CO_2 injury, too low oxygen concentration injury). Too rapid chilling or long exposition to chilling stress leads to tissue weakening, biochemical alterations and cellular dysfunctions. Often, injured products that are chilled will still look sound when remaining in low temperatures; symptoms of chilling injury become evident in a short time after they are removed to warmer temperatures. The most common symptom of freezing injury is a water soaked appearance. Too low concentrations of O_2 and high concentrations of CO_2 lead to certain physiological disorders such as internal browning in apples and pears, irregular ripening of fruits, such as banana, mango, pear, and tomato, development of off-flavors and increased susceptibility to decay (Gross et al. 2004).

Another disorder linked to long term storage is scald (apples, pears), a damage and death within fruit skin. It only occurs after relatively long periods of storage. Early in storage, fruit accumulate a chemical called alpha-farnesene; which is oxidized to a group of fruit skin toxic compounds gradually accumulated as long as the fruit are kept in storage. Some cultivars are more susceptible to scald; also hot weather in the late growing period contributes to the excessive development of alpha-farnesene (Postharvest Information Network 2010).

The overall benefit of the cold chain technology in reducing postharvest losses of FFV can be illustrated by comparing the refrigerated storage capacity with the postharvest losses: In developed countries

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[48] 1-MCP is sold commerically as SmartFresh and is approved and accepted for use in more than 34 countries (including the EU and US).

where refrigerated storage capacity per capita is 10 times higher than in developing countries, the losses are substantial lower (15% comparing to 40% in developing countries, IIR 2011). The lack of cold chain in developing countries is particularly worrying if we take into account that increasing proportion of their inhabitants live in big urban agglomerations. The world urban population is expected to increase by 72 per cent by 2050, from 3.6 billion in 2011 to 6.3 billion in 2050; most of the expected growth will be concentrated in the urban areas of the less developed regions (UN DESA 2012).

6.6. Moulds and Mycotoxins

Mycotoxins are the cause of a range of human and/or animal diseases and occur in a variety of crops (grains, roots and tubers, fruits and vegetables). The ingestion of mycotoxins can produce both acute (short-term) and chronic (medium/long-term) toxicities ranging from death to chronic interferences with the function of the central nervous, cardiovascular and pulmonary systems, and of the alimentary tract. Some mycotoxins are carcinogenic, mutagenic, teratogenic and immunosuppressive.

According to the site and time of infestation, the fungi can be divided into three groups: (a) Field fungi (b) Storage fungi (c) Advanced deterioration fungi (Gowda et al. 2010). Fusarium and Rhizopus sp. are typical field fungi. The storage fungi are Aspergillus and Penicillium. The advanced deterioration fungi normally do not infest intact kernels, fruits or roots, but easily attack damaged crop and require high moisture content.

The pre-harvest control of the fungal agents is limited by our inability to control the weather. Both insufficient and excessive rainfall during critical phases of crop development can lead to mould contamination and mycotoxin production. The very serious health consequences and the substantial economic losses attributed to mycotoxins (for example over $1 billion losses to agricultural industries in Canada, Xue 2012) clearly emphasize the need for research and development in the area of the prevention of mycotoxin contamination worldwide.

A considerable effort has been expended on the development of cereal strains which are resistant to mould growth and/or mycotoxin production. FAO (1994) was quite optimistic in this respect. However, fifteen years later, researchers (e.g. Abbas et al. 2009; Xue 2012) are much more careful in expectations, stressing that resistance breeding has not been productive yet, and cultivars with high levels of resistance are not yet commercially available[49]. In contrast, Xue (2012) is enthusiastic on bioagents: The proposal is to apply nontoxic strains of funguses to the field in a large enough quantity mid-season so that it outcompetes the toxic ones. According to Xue (2012) application of bioagents exhibited effects of about 50% reduction of mycotoxins in lab and field tests. Similarly, there are good experiences with a bioagent based AflaGuard[50] eliminating the development of aflatoxin. Many authors, like Alakonya and Monda (2013) and Ma et al. (2013), emphasize good agricultural practices (including crop rotation, management of crop residues, and timing) as an effective instrument in reducing fungal infestation.

Alakonya and Monda (2013) believe that biological protection based on bioagents outcompetening the dangerous funguses can be a pervasive solution for African countries: they suggest (i) selecting local non-toxigenic strains and registering them for mycotoxin management (ii) launching extensive education programmes to raise awareness of (small) farmers and intermediaries; (iii) content of mycotoxins (effectiveness of the measures) should be monitored; (iv) government should provide incentives for farmers, particularly the small ones, to adopt biological protection measures.

More research is needed to identify and develop fruit, vegetable and root/tuber cultivars that are resistant to fungal decay.

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[49] Some tests toward development of commercial cultivars have already started: for example see http://www.ars.usda.gov/is/pr/2010/100520.htm

[50] Offered by Syngenta - the product is actually a form of Aspergillus flavus that is benign.

The post-harvest handling of crops does, however, present another opportunity for controlling mycotoxin production. First of all, gentle and sanitary handling of any crop during harvest, postharvest procedures and in storage facilities is essential for reducing fungal decay and mycotoxin production in any crop. The identification and segregation of contaminated material is necessary. It should be pursued through the implementation of quality control procedures on field and at the delivery in the storage. Automatic colour sorting, often in combination with manual sorting, is widely used to segregate kernels, fruits or roots of abnormal appearance. Second, avoiding excess moisture and lowering temperature as far as possible will, as it was pointed earlier in this study, reduce both, the spread of funguses and the production mycotoxin (except for Alternaria sp.). Fungal growth can also be inhibited by chemical methods as application of fungicides, fumigation with ammonia, aluminium phosphide, etc., ozonification or washing in water with hypochlorite or diluted ozone.

Another method for controlling mould development is modification of atmosphere by reducing oxygen close to zero and increasing significantly CO_2. In the case of grains, it is achieved by sealing the storage bag or bin. In contrast to grains, fruits and vegetables are sensitive to low oxygen and high concentrations of carbon-dioxide, thus using these agents in protecting crops against moulds must be done very carefully and only for short time. Controlled atmosphere is not common in roots and tubers storage.

Finally, the most recent methods concentrate on the microbiological destruction (detoxification) of the mycotoxin(s) in processing. Fernandes Oliviera et al. (2013) reports positive effects of decontamination of aflatoxin by Lactic Acid Bacteria and yeast (Saccharomyces cerevisiae). In general, more work is needed to determine the fate of mycotoxins during other processing (Jackson, Al-Taher 2008).

An essential step in combating mycotoxin is the identification of the problem. It is important to state norms of mycotoxin concentration in agricultural and food products and to measure it afterwards. FAO conducted a survey on mycotoxin regulation in 2002-2003 (FAO 2004). On a worldwide basis, at least 99 countries (87% of the world population) had mycotoxin regulations for food and/or feed in 2003, which represents an increase of approximately 30 % over a decade. The most dissatisfactory situation was in Africa, only 15 countries had mycotoxin regulations, representing 59% of African population.

Measuring mycotoxin contamination of raw agricultural products requires both good sampling method and good analytical method. Laboratory high performance liquid chromatography (HPLC) has been used for the analysis of a wide range of mycotoxins. However, simple, rapid, efficient screening methods which can be handled by relatively unskilled operators are needed for practical use on small farms or by small traders in developing countries (Coker 1991)[51].

While biotechnological solutions are not ready for practical application (perhaps more resources are needed to be put into research and knowledge transfer) conservative and chemical methods needs more attention, training and encouragement for their adoption.

6.7. Institutional and other socio-economic aspects

Harvest and postharvest losses are affected by a number of natural and socio-economic factors (Table 39). These natural and socio-economic factors constitute the environment in which harvest and post-harvest technologies are developed and adopted. Commodities and their production and postharvest systems are differently sensitive to this environment and its changes. Because of the limited control over the natural factors (particularly climate and weather), technologies tend to adopt to them reducing as much as possible their negative impacts. Natural factors like sunshine, wind or relatively stable temperature and humidity underground are usually effectively exploited in the traditional postharvest technologies. Dealing with natural factors in postharvest technologies is extensively discussed in

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[51] Current mycotoxin screening tests kits cost between $180-$400 (SeedBuro 2013). It means, the instrument is too expensive to be used on small farms or at the village level cooperative.

commodity specific paragraphs (Chapter 6.3 – 6.5). In the introduction (Chapter 6.1), three socio-economic drivers of the food supply chain were mentioned. This chapter concentrates on the socio-economic production and postharvest system aspects.

Crop vulnerability to weather condition in the production and post-harvest processes is particularly important in the context of the current climate change. More frequent adverse weather events damage or destroy crops and create unfavourable conditions for the post-harvest treatment which then lead to the deterioration of crops during storage and thus to higher food losses. It calls for changing agricultural and postharvest practices which might be in conflict with traditions, experience and capacity of farmers. In addition, the need for changing farming and post-harvest practices results from new cultivars which bring obvious benefits like high yields, pest resistance or better nutritional and taste properties, but might also have other physical and biological properties (e.g. tougher ears, tiny skin etc.). The other factor pressing on farming practices is increasing environmental concern of the public: This limits for example the use of pesticides, puts pressure on using water, recycling water and plastics.

Table 39: Factors affecting harvest and post-harvest losses

Natural	*Socio-economic*
Weather and climatic conditions	Agricultural practices in the pre-harvest phase
Spread of pests (bacterial, fungal, insect, rodents)	Applied harvest and postharvest technologies
	Transport infrastructure
Physical and biological (pest resistance) characteristics of crop varieties	Human factor / knowledge & skills
Endogenous biological processes (respiration, transpiration, ripening etc.)	Scale of farming
	Integration of FSC
	Economics of production and postharvest practices (productivity, farm income, efficiency)
	Institutional and policy factors (legal framework, property rights, capacity for cooperation, etc.)

Source: Own classification

It follows from the commodity sections (Chapter 6.3 – 6.5) that harvest and postharvest technologies must be harmonised if losses are to be reduced. For cereals, potatoes and sweet potatoes, fruit and vegetables such harmonised modern technologies exist, and not only at large scale. There are many small growers[52] in developed countries who produce, store and sell quality crop. Such harmonisation rests in understanding the biological and technological process and in the coordination of activities in the growing, harvest and postharvest phases. The historical experience of farmers is insufficient because new cultivars, inputs and mechanisation as well as imported pests entered in the traditional systems. New ways of information dissemination (e.g. mobile phone internet access), education and training are needed.

Cereal, potato and sweet potato harvest and postharvest can be largely mechanised, labour requirements have declined significantly over the last decades. Harvest of yam, cassava and fruits and vegetables remains largely labour intensive. The postharvest treatment of most crops tends to be organised on farms particularly in developing countries. Nevertheless, cooperative postharvest facilities are common too – perhaps more in developed than in developing countries. There are also commercial storages,

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[52] Often part-time farmers or hobby farmers, supplying local markets.

usually owned and organised by large merchants, processors or by the government. In general, there are benefits of scale. Therefore, modern technologies tend to be adopted by large businesses. Modern technologies require a certain degree of integration within the food chain because postharvest operations depend also on the final use of the crop. In addition, investment costs are rather high and assets specific (particularly for roots and tubers and for fruits and vegetables), thus good links to market are necessary (preferably long term contracts). Storing crop enables producers to market their production when prices are good. In contrast, small farmers who do not have suitable storage facilities must often sell their surplus production immediately after harvest.

It was indicated that traditional technologies do not provide sufficient protection of stored crops, and therefore, the losses are high. On the other hand, good technologies are available and there is increasing offer of such which in their scale fit to the needs of small farmers – especial in grains and tubers. Changing storage technology depends on many factors. Subsistence farmers (who have very limited cash) will always find buying storage equipment as less preferable than making it from a variety of locally available materials like straw, wood, bamboo, reeds, mud, bricks, cow dung etc. Farmers might lack knowledge and confidence that new technology will really reduce losses significantly.

It is not only the storage facility and equipment which will solve the problem of crop losses. It will also require management and additional knowledge. The farmer must assure that the moisture content of grain is sufficiently low, that crop put in the storage place is clean and healthy. Disinfection of the storage place, suitable storage structures including containers will be needed. Continuous monitoring and control of temperature, humidity, air circulation and atmosphere in the storage will be required. Small commercial farmers might need flexible postharvest and storage facilities, since the crop and volume of harvest vary from year to year and also the time for which grain or tubers are kept on the farm before selling might be highly variable. Thus these farmers will be reluctant to invest in a technology which might provide good and save long term storage but for high (investment) cost. As already mentioned, shared warehouses, silos or refrigerated and controlled atmosphere storages (at village level or in a cooperative of producers) might be an option, but there must be a commitment of all participating farmers to assure quality and safety standards of their crops put in the joint storage. In addition, sufficient social capital for a collective action is needed.

Another option is to bring harvested grain or tubers as soon as possible to the large modern well operated storages (central storages). Indian cereal storage system represents rather successful case in this respect (e.g. Naik, Kaushic 2011). Price guarantee makes the flow of grain to storages easy. Moreover, the participating agencies provide cleaning, handling and transportation, procurement and distribution, disinfection services, fumigation services and other ancillary activities, i.e. safety and security, insurance, standardization and documentation (India Agronet 2009). The weakness of the Indian cereal system is (according to Singh, 2010) that (a) it is entirely oriented on food security of urban areas, while rural areas, and in particular very small farmers, might be short in grain, (b) in order to cope with increasing production (stimulated by governmental subsidies – price guarantee) the storehouses do not conduct according to the recommended ("scientific") practices and a lot of grain is spoiled.

Small Indian farmers can also deliver their potato crop to "scientific" storages and they can receive easy marketing credit against the stored produce (AGMARKETNET). The system is similar to the system for cereals, however, relying more on private storages. Because storage rents are administratively fixed on one side and potato prices highly volatile, the system performance is rather variable. The fixed storage rents discourage private investors (Dahiya et al. 1996) and price risk discourages farmers to use these storage facilities (Fuglie 1999).

International development assistance programmes has tended to support 'modern' capital-intensive systems (Coulter 1991): silos/elevators against warehouse or bulks against sacks. There are however warning cases that such investment plans paid little attention to local conditions resulting in low or no effect (eg. Pakistan, Coulter 1991, or Millig Corporation of Tanzania, FAO 1994).

Postharvest technology, its development and adoption, depends also on the whole sale and retail sectors and consumers. This can be well illustrated on the fresh fruits and vegetables sector. Reefs (2010) describes differences between the traditional FFV marketing systems and the modern one. In the developed countries, FFV are produced on large farms, or farms associated in marketing cooperatives. The FFV supply chain exhibits strong vertical relationships. The consumption is rather continuous (also due to the availability given by the international trade). Under these circumstances, farmers and their cooperatives are ready to invest in postharvest technology. In contrast, traditional systems rely on small farmers and several levels of rather small intermediaries. Although the system is able to deliver FFV in the urban areas, it provides little incentives and guarantee for the investment in postharvest technology. This however is needed in order to reduce losses. Transport is almost entirely in ambient trucks and roads can be very congested and poorly maintained in some areas. Cold stores (if any) are often multi-user with owners providing a service. Various fruits and vegetables might meet in one storage room with adverse effects each on the other.

Solutions for decreasing postharvest losses might offer an integrated approach from “seed to supermarket shelf” (Hewett 2006). Actually, cold chain can function only as fully implemented, i.e. refrigerated storage – refrigerated transport – refrigerated retail store. Reardon and Minten (2011) argue that recent rapid development of private supermarket chains in India (annual growth by 49%) might represent the necessary power able to transform gradually the whole supply chain in the near future. These retailers concentrate on the needs of the growing middle class whose diet has changed in favour of fruits and vegetables over last 20 years. According to Reardon and Minten (2011), supermarkets, by their push on the supply chain, can stimulate vertical integration which will have capacity to provide a framework for private investment in the FFV cold chain. They call this process top-down revolution in the food supply chain. Perhaps we can generalize it for the other two commodity chains too.

In developed countries, we can expect continuing increasing concentration and vertical integration in the fruits and vegetables sector on one hand, as well as an expansion of short chains delivering local produce to local markets on the other hand. Concerning the former, the strong capital position of the integrated chain will allow investment in progressive technologies, research and education. Although direct marketing will be continue to grow for some time, it is very likely keep the character of niche market of seasonal production. This will challenge sustainability of farm income.

It is more or less clear that not all farmers in developing countries will be able to cope with the knowledge requirements and requirements for standardisation and safety procedures, even if an effective extension service is be established and available. In addition, vertical integration as well as investment costs will require growing in size which under property rights restrictions in many countries will be achievable only by horizontal cooperation. This will require social capital and taking risk in pooling financial capital and profit. Thus it is very likely that the crop sector modernisation will go hand by hand with structural change which might result in a separation of the progressive urban oriented food chain and marginalised rural semi-subsistence farming.

The dominance of poor farms (either peasant households or disrupted collective farms) represents a constraint to the spread of mechanisation and advanced technologies in the crop harvest and postharvest process. Often such farms are not integrated in markets; there are many intermediaries and the system is largely inefficient. Hodges et al. (2010) following World Bank (2010) argues that some of the improvements for reducing post–harvest losses in least developed countries will need to take the form of public ‘goods’ including market organisation and infrastructure such as the development of networks of all-weather feeder roads so that crops can get to market, a problem especially acute in Africa.

Past experience shows that the support system cannot be exclusively technically focused (Parfitt et al. 2010; Kitinoja et al. 2011); in contrary, more types of intervention are needed: “institutional” providing effective rules, knowledge transfer support, improved access to credits and often direct market intervention providing stabilisation through temporary storage of surpluses. In addition, producers must be guided to see a clear direct or indirect advantage, particularly financial benefit.

7. OPTIONS FOR ACTION

Spread and implementation of existing knowledge, technologies and best practices, and investment in new agricultural science innovations and production system approaches are needed to achieve an increased food production in a sustainable way. Overall objective is the contribution of European food production to feed the increasing population worldwide. Sustainable intensification should be reached by

- reducing the yield gap through improving crop production management,
- increasing the yield potential by plant breeding, and
- reducing crop losses.

Sustainable intensification means simultaneously raising yields, increasing the efficiency with which inputs are used and reducing the negative environmental effects of food production, under social and economic beneficial conditions. Options for action to support sustainable intensification in the EU, including plant breeding, are worked out in chapter 7.1. The next chapter analyses options for action to reduce harvest and post-harvest crop losses. Concluding, chapter 7.3 describes major issues for the contribution of agriculture to food securityat the global level.

7.1. Sustainable intensification in the European Union

Based on the assessment of different crop production systems and considering the very different settings of European farming systems, overall priority tasks in the frame of sustainable intensification are:

- Increasing input use efficiency especially in intensive production systems to improve their environmental performance and to maintain their production potential;
- Increasing productivity in extensive production systems without compromising their environmental services;
- Including marginalised farmers (e.g., semi-subsistence farming) in productivity improvement to preserve their contribution to food supply and for accompanied social and environmental benefits;
- Progresses in plant breeding which addresses the challenges ahead and different farming systems;
- Supporting public sector crop breeding and genomics programmes that emphasise longer term objectives that cannot be expected from the private sector;
- Stronger focus on maintenance and enhancement of soil fertility and exploitation of agro-ecological mechanismto stabilize achieved high yield levels in favourable areas, to realise more of existing yield potentials, and to increase the resilience of farming systems;
- Exploring possible combinations and mutual benefits between input use efficiency and soil fertility improvement approaches (e.g., precision agriculture and conservation agriculture);
- "Down-size" of high-tech approaches(e.g., precision agriculture) so that progress in different farming systems can be achieved;
- Strengthening of participatory approaches to improve transfer of knowledge and innovations;
- Considering that wider spread of specific agricultural production systems (e.g., organic farming) could support the change of diets with lower consumption of meat products which induce high demand of land;

7.1.1. Building awareness

Global food crop security as a priority is a grant challenge and demand long term action (Royal Society 2009). Possible contributions of the European agriculture to increase food production have to be recognised and put into practice. Sustainable intensification needs political commitment at European and Member State level, supported by informed dialogue with farmers, other stakeholders and members of the public. Objectives of sustainable intensification can only be reached with active involvement of key stakeholders including ministries, governmental agencies, local authorities, research bodies, farmer organizations, non-governmental organisations and the food industry.

New approaches in crop production are partly contrary to the experiences and practices of the last decades with specialisation and high external intensification in the European agriculture. A major barrier to wider adoption of promising crop production systems such as conservation agriculture, agroforestry and integrated crop-livestock production is limited awareness among farmers, scientists, administrators and politicians. Empirical evidence of feasibility and of benefits is a key to argue farmers into changing their production practices.

7.1.2. Research, development and demonstration

Recent scientific and technological advances and practical experiences offer significant new opportunities to address challenges of sustainable intensification. Major options for action concerning research and development for agriculture are:

> After decades of de-investment in public agricultural research, more public money (EU and Member States) is required, in addition to existing research spending. Especially, support should be increased for ecosystem-based approaches, agronomy and the related sciences that underpin improved crop and soil management.

> Food production research should focus on raising yields in conjunction with maintaining and enhancing ecosystem services. Sustainable intensification will often need specific measures (e.g., public research programmes) to incentivise research that produces public goods and longer-term results.

> Research should take a stronger focus on maintenance and enhancement of soil fertility and exploitation of agro-ecological mechanism to stabilize achieved high yield levels in favourable areas, to realise more of existing yield potentials, and to increase the resilience of farming systems.

> Possible contributions of the discussed crop production systems to climate change mitigation and adaptation is an important issue.

> Crop production systems approaches should be in the centre of research activities. Single technologies and practices promise only restricted advances. Approaches that combine different technologies and practices will produce real progress.

> There is a lack of received knowledge and research on former Agroforestry systems that have now largely disappeared. This includes their residual existence, their functioning and their potential for modernisation.More research activities and institutional interest on Agroforestry is needed in the EU.

> Long-term agronomic research projects at both farm and research levels throughout the EU are needed because the impacts of greater shifts in crop production (such as with conservation agriculture, organic farming, agroforestry and integrated crop-livestock systems) needs time to manifest.

> Agricultural research should address the different European farming systems specifically. Research activities should also include extensive farming and small-scale farming (e.g., semi-subsistence farming) in Europe, to preserve their contribution to food supply, to enhance their productivity and to sustain their environmental and social benefits.

> Boundaries of the past between public funded basic research and private funded applied research as well as between research institutes and universities as dominant sources of knowledge and innovation and the farmers and commercial sector as adopters get more and more blurred. This demands new forms of cooperation and knowledge exchange. Without public funded incentives for new cooperations, the agricultural knowledge system could become increasingly fragmented.

> Research communities should open up, and mutual learning should be encouraged between precision agriculture, conservation agriculture, organic farming, agroforestry and integrated crop-livestock system research, based on common points in objectives and practices.

> Interdisciplinary and participatory research should be strengthened. This task has to be taken up by the scientific system as well as by funders. At European level, a network "Participatory Research for Global Food Security" could be established in the frame of the Horizon 2020 programme (TAB 2011, p. 22).

> In precision agriculture, scientifically and economically sound decision support systems are a a major bottleneck. Therewith, a research focus should be on precise identification input utilisation and yield determining factors, their interaction, and their translation in crop management decision. Important step is to convert side specific rules in generally valid rules.

> The principle of side-specific application of production inputs should be made available for the different European farming systems. Therefore, "soft" PA concepts should be developed which depends mainly on inexpensive technologies or visual observation of crop and soil, and management decision based on experience and intuition. Open question is how high-tech and low-tech approaches could learn from each other.

Additionally, specific research options, with the aim to strengthen the contribution of plant breeding to sustainable intensification, are:

> Funders should support public sector crop breeding and genomics programmes to understand, preserve and enhance the germplasm of priority crops and train the next generation of plant breeders. Public sector support for breeding needs to emphasise on longer term strategic approaches which cannot be expected from the private (Foresight 2011).

> An elementary task for hybrid breeding research is to reveal the molecular basis of the heterosis effect. This is in progress and could extremely contribute to improving the hybrid breeding method in the near future.More efforts have to be made in identifying the best combinations of parental lines for creation of high-performing hybrids. This is in progress by using modern breeding approaches such as molecular markers or novel genotyping approaches using DNA sequencing methods in hybrid breeding programs.

> Marker-assisted selection and SMART breeding are very promising breeding technologies, but not fully developed yet.Especially new genomic selection technologies based on DNA sequence information offer great potential for a distinct more precise candidate selection and breeding success. Support for further research should be one main focus in public breeding research support.

> Organic breeding in the EU is highly heterogeneous, overall still in an early stage of development. Progress in organic breeding is needed so that organic farming can take part in overall increase of yield potentials. Results from organic breeding could also be of relevance for other extensive farming systems.

> Important for organic breeding is a transparent assessment of modern breeding technologies in regard to their compatibility with the principles of organic farming. Aim should be a common understanding which breeding approaches can be used in organic breeding.

> Participatory plant breeding was developed and deployed to better serve the needs of small-scale farmers in developing countries, mainly in marginal regions. Participatory plant breeding could be an approach toaddress European semi-subsistence farming which would need public support.

> With mainstreaming of agro-ecological approaches and more local differentiation of crop management, an overall closer collaboration of plant breeders and farmers could become more important.

- European breeding research should contribute to the worldwide dissemination of modern breeding technologies (tissue-culture techniques, marker-assisted breeding), especially to developing countries, by development of low cost methods, knowledge and technology transfer, and internationalprogrammes, in collaboration with Consultative Group on International Agricultural Research (CGIAR).

7.1.3. Knowledge and technology transfer

Investment in research and development is not enough in itself.Effective knowledge and technology transfer to the farming communities, using a combination of scientific and practical expertise, is of high importance. New approaches take too long to arrive on the ground, and the needs of practical farming are not communicated sufficiently to the scientific community (EC 2012).

Agricultural knowledge and innovation systems (SCAR-AKIS 2012), understood as a set of public and private organisations dedicated to research, education and training, extension, and their interaction with farmers as user and generator of knowledge and innovations, should be involved as a whole in sustainable intensification. The Common Agricultural Policy should use parts of its budgets to encourage innovation-orientated research and activities, including empowerment of (group of) farmers and support for knowhow exchange in Europe (SCAR-AKIS 2012).

Extension services show high diversity between EU countries. Some countries have completely privatised their extension services, while in other countries public funded extension services still exists (Hermans et al. 2010). The revitalisation of public funded extension services to increase the skills and knowledge base of agricultural producers is critical in the case that innovations of sustainable intensification should reach farmers in broad-scale. Otherwise, new knowledge and innovation tends to be restricted to economically advanced farms which are able to afford commercial advisory services.

The current focus on single crop systems within agricultural research institutions and universities reduces the advice and training available to farmers wishing to manage for example agroforestry or integrated crop-livestock systems (Eichhorn et al. 2006). Therewith, research and transfer systems should develop in a coordinated way.

7.1.4. Communities of practice

A single strategy for up-scaling of advanced crop production systems (precision agriculture, conservation agriculture, agroforestry systems or integrated crop-livestock systems) will not work: The strategic approaches and principles must be tailored to countries, regions, farming systems or even local sites, reflecting specific technical, economic and social conditions.

For up-scaling, a close partnership from the start among diverse stakeholders in adapting, promoting and supporting uptake –farmers and their organisations, research, extension services, service/input/credit providers, government agencies, NGOs, etc. – should be ensured, to support knowledge and innovation co-creation. This demands institutional learning and new networks to combine top-down and bottom-up knowledge creation and transfer mechanisms.

For conservation agriculture, the concept of “Community of Practice” (CoP) has emerged to improve both knowledge and practice (FAO 2008).The premises for such Community of Practice are (STOA 2009):

- The improvement of both theory and practice is greater from a *continuous interaction* between researchers and practitioners than from following the previous concept of a linear process where knowledge is generated and validated separately from practice, being subsequently ‘extended’ to practitioners.
- There is greater productivity from having *multi-sectoral cooperation* than having a standard ‘division of labour’ because different kinds of institutions (public sector, private sector, NGO, academic,

grassroots, etc.) have respective comparative advantages to contribute to a collective enterprise and learn from each other.

> There is great power in bringing together *like-minded individuals* who operate from diverse institutional bases, who have agreed on the general goal even if they contribute to different ideas and values of the means for achieving this; excitement and energy as well as information can be generated from heterogeneity that is encompassed within an 'envelope' of broad agreement leading to convergence of community members' perceptions and action.

The concept of "Learning and Innovation Networks for Sustainable Agriculture" (LINSA) is a similar network approach for AKIS. It describes thematically-focused learning networks that are made up of different actors, within and outside the formal, institutionalised AKS. These approaches need organisational and financial support, and should be a model for the different agricultural production system approaches.

The European Innovation Partnership (EIP) "Agricultural Productivity and Sustainability" (EC 2012) offers new possibilities to establish in the frame of the EIP Communities of Practice as operational groups at cross-border or Union level (Art. 62, EC 2012). EIP network facility can be important as a mediator enhancing communication between science and practice, and fostering cooperation.

7.1.5. Incentive programmes

Conversion to improved crop production systems are often connected with initial investments, costs and risks of learning and adapting to local conditions, and delayed improved returns. Especially, the conversion to agroforestry or integrated crop-livestock systems demands high investments in the start. The conservation to organic farming is also with higher costs associated.

Under Pillar 2 of the Common Agricultural Policy, payments for the conversion to organic farming (and maintenance) are already possible in the frame of agri-environmental measures (Sanders et al 2011). The support schemes in the Member States show large variations and partly weaknesses such as payment rates, scheme discontinuities, scheme access problems, design and application of eligibility criteria (TAB 2012, p.67).

Under Pillar II of the Common Agricultural Policy, support for the establishment of agro-forestry systems, conversion and maintenance of organic farming (Art. 24, 30), and agri-environmental measures is foreseen in the new regulation (period 2014-2020) for rural development by the European Agricultural Fund for Rural Development (EAFRD) (EC 2011b). After the outstanding adoption at EU level, the next important step is implementation of consistent programmes in the Member States which address also the importance of sustainable intensification. In the frame of agri-environmental measures in Member States, incentive programmes should be implemented to encourage the adoption of conservation agriculture and support theconversion phase. In the moment, support for conversion to integrated crop-livestock production is not foreseen. This should be amended in order to make use of the potentials of this approach.

7.1.6. Enabling CAP reform

Technological developments with different stages of mechanisation and increased labour productivity, and advances in synthetic fertilizers and pesticides were major driving forces for specialisation and high external input intensification in the last decades. Until the decoupling, the subsidy regime of the Common Agricultural Policy (CAP) has favoured this process.This led indirectly to a reduction in crop association by favouring single crop systems and in farms combining crop and livestock production.

With the decoupling of direct payments, the support scheme of direct payments to farmers is neutral in regard to the applied crop production systems. The proposed greening components to be included into the direct payment scheme of Pillar I will not give a strong incentive for agro-ecological oriented production systems or components such as more diversified crop rotations (Heinrich et al. 2013).

A more enabling surrounding for sustainable intensification would demand a longer-term transformation of the CAP with a phasing out of direct payments, similar to the "refocus scenario" discussed by the Commission in preparation of the on-going CAP reform (EC 2011a, p. 4) or for example the CAP reform proposal of a coalition of German stakeholders (Euronatur, AbL 2010). Reasoning is that public payments should be linked to the provision of societal benefits. Approaches for sustainable intensification could fulfil this claim because the longer-term productivity, social and environmental gains are not honoured in total by market prices. Difficulty is to achieve a broad consensus on agricultural production systems which are sustainable or on criteria for environmental-friendly production measures.

7.1.7. Alignment of regulations

Some specific regulation issues with relevance for sustainable intensification or progress in plant breeding could be identified:

> *Appropriate regulation of agroforestry*: Overall, regulations separate agriculture and forestry into distinct land use categories. Agroforestry systems fall between these two types of land use. National legislation on forestry can be a barrier of the establishment of Agroforestry (Eichhorn et al. 2006). Legislation in the Member States is on the way to amend this.

> *Review of the EU legislation on the marketing of seed and plant propagating material (SPPM)*: In this frame, a special regulation for the authorization of heterogeneous, locally well adapted varieties (landraces), for example as so-called "niche varieties", should be introduced.

> *Regulation of new plant breeding technologies in the frame of GMO regulation*: New plant breeding techniques (such as cisgenesis/intragenesis, Chapter 5.3.5.) are associated with legislative uncertainties of the GMO classification. Contrary opinions on the legal status are developing in science and society. Therefore, a broad dialogue should be initiated with the aim to clarify the legal status of new plant breeding techniques in the frame of the GMO regulation.

> *Patenting of crops*: It should be guaranteed that patents can exclusively be hold on inventions but not on gene sequences that are also included in traditional varieties. Otherwise, increasing yields by conventional breeding and non-GMO techniques could be hindered severly.

7.2. Reducing crop losses

Harvest and post-harvest losses are an important issue on the global level. Their reduction can contribute to the local as well as global food security. Food losses until the farm gate include handling at harvest and post-harvest, storage, and transport and distribution by farmers. The amount of food losses is dependent from natural factors like climate, weather, crop biological characteristics and spread of pests, and on the development state of food supply chains, with their specific post-harvest technologies, marketing organization and existing infrastructure.

The principal precondition for an effective reduction of harvest and postharvest losses is to *increase awareness among farmers and the other actors in the food supply chain* about the importance of the issue. Collecting information on the extent, nature and causes of harvest and postharvest losses is a part of it. These data should build a base for *long-term strategies for reduction of crop losses of international bodies, national and regional authorities as well as non-governmental donor organisations*. Establishment of national action plans and bodies/programmes unifying research and extension (like in India, Brazil, Argentina) is recommended in countries where postharvest losses are particularly high.

Actions for reducing post-harvest losses should be tailored to their nature and causes, to the affected crops and to beneficiaries and their socio-economic characteristics. Nevertheless, there are some common options/ activities like enhancing research and development or improving physical infrastructure which will pay off in any circumstances.

Private and public R&D should be encouraged in three lines:

> Selection and development of cultivars resistant or less susceptible to pests
> Biological protection against pests, particular fungal pest producing mycotoxins
> Small scale technical equipment (mechanisation, storage bins and sacks, buildings, etc.) which uses as much as possible locally available resources (materials and energy e.g. solar or wind energies)

The *infrastructure enhancement* should aim first of all at roads and railways, but attention should also be paid to clean water supply, energy supply or ICT (internet, mobile phone). Water recycling should be part of any postharvest operation using water in large quantities. Particular attention should be paid to solar energy and energy released from cooling down the crop in refrigerated storages. Good practice guidelines should be issued on the last two topics.

In many cases postharvest losses, particularly storage losses, have their origin in the growing period, harvest and postharvest handling. The problem usually rests in low coordination/integration of these processes, while they individually produce little losses. Often it does not require further research, yet the existing knowledge and experience are to be deployed in agronomic, harvest, postharvest treatment and storage practices in an integrated way (crop rotation, removal of crop residuals, gentle handling, use of proper containers and trucks, cleaning, inclusion of curing or controlled ripening etc.). *Methodological guidelines and training on good practices* should be provided. These should be tailored to the particular crop (taking into account differences among cultivars), locality and should respect human and financial capacities of beneficiaries (subsistence farmers, commercial farmers, small traders, etc.). The process should be *supported by extension service and help-lines* accessible by mobile phone or by internet. In some cases it might require also investment in the equipment or an establishment of specific services (e.g. laboratories where farmers can let test their samples).

Similar approach should be adopted when introducing (spreading) new technological advances (crop varieties, mechanisation, biological protection, refrigerated storage etc.). Here, substantial investment might be needed for which farmers will need financial resources.

Farmers can invest in new technologies only if it will be rewarded by higher income from the market. Thus the spread of promising technologies is underlined by functioning markets (FSC). The *government and local authorities should engage in improving the marketing system* in several ways:

> Establishing or improving market rules providing standards, contract and payment terms, guarantees and safeguards, and promoting their enforcement;
> Promoting development of appropriate market infrastructure (including central markets, appropriate storages, refrigerated transport means etc.);
> Promoting market information system particularly aiming at better producers' decisions about timely supply to markets, avoiding or at least reducing seasonal gluts.
> Encouraging and securing participation of small-scale famers. It might involve incentive programmes like price guarantee, tax exemption, credit supply or temporary storage provision.

Naturally, developed food markets tend to be urban and export oriented. The government policy should nevertheless provide *incentives for the development of rural markets* in their specificities. If higher production is encouraged by policy incentives, the government should coordinate, and promote investment in storage facilities that they keep pace with growing output.

Farmers should not be encouraged to invest, particularly by taking credits, if they are not integrated in the functional market, even if such investment promises food saves. Alternative solutions should be found for subsistence farmers (donor programmes or alternative technologies).

Education and training, extension but also *exchange of experience among farmers and information flows along FSC* are essential elements of crop losses programmes. Similarly, horizontal and vertical cooperation is needed. In many case, it is efficient to share mechanisation or storage facilities, in some cases unavoidable if postharvest losses are to be reduced and food (crop) effectively delivered to distant consumers (particularly it concerns fresh fruits and vegetables). Starting the cooperation in the both directions, with information and experience exchange and joint education programmes, might be a building block for tougher business relationships.

7.3. Global perspective: Food security issues

Achieving and securing food security for the growing world population is a global task. Development of smallholder agriculture in developing countries will play a major part. Although this study has not assessed policies for global food security, some important issues can be highlighted. These include (CFS-HLPE 2013; IAASTD 2009a; STOA 2009; World Bank 2007):

> *Food pricing policies* should give farmers a fair and stable return for labour and investment.

> *Land policies* should guarantee tenure and/or ownership security for smallholder farmers over land and natural resources, including the implementation of the "Voluntary Guidelines on Responsible Governance of Tenure of Land, Fisheries, and Forests" (FAO 2012b) and the "EU Land Policy Guidelines" (EU Task Force 2004);

> Climate change and growing water scarcity require policies and investments to improve *access to water and irrigation*, which is a major determinant of land productivity and yield stability. There are many opportunities to revamp existing schemes and expand small-scale schemes and water harvesting.

> *National agricultural research and extension systems* should be upgraded, targeted specifically to the needs of smallholders. The main objective would be to increase productivity and resilience through diversification and agro-ecological approaches. Formal, traditional and local knowledge need to be integrated. Therefore, a high level of investment in national and international agricultural research should be achieved.

> Policies should enable and support *farmer organisations*. Collective action by producer organisations can facilitate knowledge and innovation exchange, strengthen farmer position in input and output markets, and increase representation in national and international policy forums.

> Better *access to financial services* for small-scale producers is urgently needed. This includes facilitating monetary transactions such as mobile-phone based money transfers, safe saving deposits, low-priced credits, and insurance such as index-based weather insurance.

> Policies should give priority to *linking smallholder farmers to* domestic, national, and regional *markets*. Market failures and price volatility are major disincentives for smallholder investment. Developing market linkages requires investment support over the food supply chain.

> Rural people need adequate access to *education, health services, water and sanitation, and social protection*. Public investment in these services supports agricultural development.

GLOSSARY

Allogemic species	Species that cross-fertilise; opposite of autogamic species that self-fertilise.
Annual Work Unit	One Annual Work Unit (AWU) corresponds to the input, measured in working time, of one person engaged in agricultural activities in an agricultural unit on a full-time basis over an entire year. Output per AWU is a particle productivity indicator (see Labour Productivity).
Arable Land	Arable land, in agricultural statistics, is land worked (e.g., ploughed or tilled) regularly, generally under a system of crop rotation (EUROSTAT).
Autogamous Species	Species that self-fertilise; opposite of allogamous species that cross-fertilise.
Blue water	Water supply with liquid water from rivers, lakes, wetlands and aquifers,which can be withdrawn for irrigation and other human uses.
Cereals	Cereals include Wheat, Rice Paddy, Barley, Maize, Popcorn, Rye, Oats, Millets, Sorghum, Buckwheat, Quinoa, Fonio, Triticale, Canary Seed, Mixed Grain and Cereals Nes (FAO 2012a).
Cisgenic Plant	Plant that contains one or more genes of a related species that have been directly transferred via genetic modification techniques.
Clonal Variety	Variety that is propagated vegetatively (asexually) (e. g. potato); the individuals of a clonal variety represent genetically identical clones of the donor plant which was propagated.
Coarse Grains	Coarse Crains include Barley, Maize, Popcorn, Rye, Oats, Millets, Sorghum, Buckwheat, Quinoa, Fonio, Triticale, Canary Seed, Mixed Grain and Cereals Nes (FAO 2012a).
Drought	Drought is a natural phenomenon. It is a temporary, negative and severe deviation along a significant time period, and over a large region from average precipitation values (a rainfall deficit).
European Size Unit (ESU)	One ESU has been defined as 1,200 € of standard gross margin since 1984 in the EU.
Gamete Cells	Haploid cells produced by sexual propagating organisms; serve as the basis for sexual propagation; by combination of two gamete cells a diploid cell forms from which a new organism can arise.
Genetic Map	Shows the linear alignement of known gene loci across chromosomes of an organism; distances between loci are statistically estimated and can not be equalized with physical distances; only the approximate position of the loci are known but not the DNA sequence.
Gini Coefficient	The Gini coefficient measures the inequality among values of a frequency distribution. A low Gini coefficient indicates a more equal distribution, with 0 corresponding to complete equality (for example, all farms have the same size), while higher Gini coefficients indicate more unequal distribution.

Genetically Modified (GM) Crop	Crop that contains one or more genes that have been directly transferred in the crop genome via genetic modification techniques.
Green water	Water supply by soil moisture generated from infiltrated rainfall that is available for root water uptake by plants, and which constitutes the main water resource in rainfed agriculture.
Haploid	Haploid means that a cell core (nucleus) only contains one set of chromosomes.
Harvested Area	Data refer to the area from which crops are gathered. Area harvested, therefore, excludes the area from which, although sown or planted, there was no harvest due to damage, failure, etc. If the crop is harvested more than once during the year as a consequenceof successive cropping (i.e. the same crop is sown or planted more than once in the same field during the year), the area is counted as many times as harvested (FAO 2012a).
Heterogeneous population	A population that is phenotypically not uniform.
Heterozygous population	A population whose individuals have unequal genomes/unequal gene characteristics.
Homogzygous population	A population whose individuals have equal genomes/gene characteristics.
Hybrid variety	The progeny of a cross of two homozygous inbred lines; hybrid varieties show superior characteristics to their parental lines which is discribed by the term "heterosis effect".
Intragenic Plants	Plants that contain one or more genes of a related species that have been directly transferred via genetic modification techniques; the difference to cisgenic plants is that transferred genes have artificially been modified in intragenic approaches.
Labour Productivity	Labour Productivity is the ration of output to labour input in a production process and represents partial productivity index. Agricultural labour productivity is measured as aggregated output per agricultural worker.
Land Productivity	Land Productivity measures the aggregated output per harvested area. Land Productivity is a partial productivity index.
Landrace	A landrace represents a local variety of a plant species that is well adapted to the environment it lives in.
Line variety	A self-pollinating plant community produced by self-fertilisation techniques; all individuals are genetically identical.
Marker	Molecular markers are short, clearly detectable sections in the genome whose positions on the chromosomes are defined.
Marker Assisted Selection	Marker-assisted selection (MAS) describes the approach to select favourable genotypes based on genotypic (marker) data.
Monogenetic Inherited Trait	A trait that is only affected by one single gene which determines its expression and characteristic.

Mutation	Spontaneous or via mutagens experimental induced qualitative or quantitative changes in the genome (also calledmutagenesis).
Oilcrops	Oil-bearing crops include both annual (usually called oilseeds) and perennial plants whose seeds, fruits or mesocarp and nuts are valued mainly for the edible or industrial oils that are extracted from them. They include: Castor oil seed, Coconuts, Cottonseed, Groundnuts, Hempseed, Jojoba Seeds, Karite Nuts (Sheanuts), Linseed, Melonseed, Mustard seed, Oil palm fruit, Oilseeds, Nes, Olives, Palm kernels, Palm oil, Poppy seed, Rapeseed, Safflower seed, Seed cotton, Sesame seed, Soybeans, Sunflower seed and Tung Nuts (FAO 2012a).
Phenotype	The appearance of an individual; the phenotype represents the sum of effects of all traits of an individual.
Open-pollinated variety	An open-pollinated plant community is produced by cross-fertilisation techniques; the individuals of a open-pollinated variety are more or less heterogeneous and heterozygeous.
Polygamy	Multiplication of the stock of chromosomes of a cell.
Polygenetic inherited trait	A trait that is affected by several or numerous genes that interact amongst each other and/or with the environment; these interactions determine the expression and characteristic of the trait.
Protoplast	Protoplasts are cells without a cell wall; the degradation of the cell wall is carried out by special enzymes.
Pulses	Pulses are annual leguminous crops yielding from one to 12 grains or seeds of variable size, shape and colour within a pod. They are used for both food and feed. The term "pulses" is limited to crops harvested solely for dry grain, thereby excluding crops harvested green for food (green peas, green beans, etc.) which are classified as vegetable crops. Also excluded are those crops used mainly for oil extraction (e.g. soybean and groundnuts) and leguminous crops (e.g. seeds of clover and alfalfa) that are used exclusively for sowing purposes. They include Bambara beans, Beans, dry, Broad beans, horse beans, dry, Chick peas, Cow peas, dry, Lentils, Lupins, Peas, dry, Pigeon peas, Pulses, nes, and Vetches (FAO 2012a).
Quantative Trait Loci	A region in the genome that has an effect on the expression of a polygenic trait; the calculated effect results from statistical estimations based on genetic analyses (e. g. marker analysis).
Root and Tubers	Roots and tubers are plants yielding starchy roots, tubers, rhizomes, corms and stems. They include Potatoes, Sweet Potatoes, Cassava, Yautia (Cocoyam), Taro (Cocoyam), Yams, Roots And Tubers Nes. (FAO 2012a).
Standard Gross Margin (SGM)	The SGM is the difference between the value of the agricultural output (crops or livestock) and the cost of inputs required to produce that output. The sum of all the margins per hectare of crop and per head of livestock in a farm is a measure of its overall economic size.
Tissue culture techniques	All tissue culture based methods follow the principle to cultivate single plant cells, tissues or organs in special culture medium *in vitro* in order to generate plant organs or whole plants.

Total Factor Productivity	Total Factor Productivity is usually defined as the ration of total output to total input in a production process. In agriculture, output is composed of multiple commodities produced by multiple inputs in a joint production process.
Transgenic Plants	Crop that contains one or more genes that have been directly transferred in the crop genome via genetic modification techniques; the genes can origin from any organism.
Utilised Agricultural Area	Utilised agricultural area (abbreviated as UAA) describes the area used for farming. It includes the land categories arable land, permanent grassland, permanent crops and other agricultural land such as kitchen gardens. The term does not include unused agricultural land, woodland and land occupied by buildings, farmyards, tracks, ponds, etc. (EUROSTAT).
Water scarcity	Water scarcity is a man-made phenomenon. It is a recurrent imbalance that arises from an overuse of water resources, caused by consumption being significantly higher than the natural renewable availability.

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Annexes, a summary and an 'Options brief' related to this study are also available.

The STOA studies can be found at:
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