3. Novel techniques in food production

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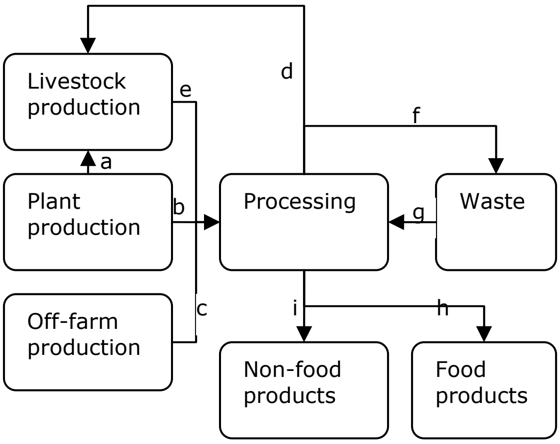
The creation of new techniques has been essential to the survival of human communities throughout history. The masterpiece *Mappae Mundi* (de Vries and Goudsblom, 2004) provides plenty of examples of how empires collapsed when novelty creation did not keep pace with changing social and natural conditions. In a rapidly changing world we need novelty more than ever. We tried to provide a selection of the most important novel techniques that will determine the food supply for the next 25 years.

Figure 2 below gives an outline of the topics discussed. On the left side, the three major pools of raw production are shown. Techniques that might be able to improve on-farm plant biomass production, on-farm livestock production and off-farm biomass production like marine products and algae are discussed. In the flowchart, the a-arrow indicates the direct flow from plant production to livestock production. This flow occurs when livestock is grazing. In most other cases, the biomass production will be processed before it is suitable for human or animal consumption. The processing box includes any activity that alters the raw product, like drying, cooking or slaughtering. Processing might be done on-farm or in factories. In addition, we describe the gains that can be expected from boosting the efficiency of food processing in the future. We will also explore new possibilities for the re-use of waste caused by processing. Subsequently, we discuss the bio-refinement technique, which in fact is a new way of processing plant products in order to make fodder and non-food products. Lastly, we will look at the possibilities of replacing meat by factory-processed plant products.

Figure 2: Flowchart of processes involved in farm biomass production



3.1 Increase in farm crop biomass production efficiency

This section deals with the plant production part in the above flowchart. New high-yielding varieties, increased fertilizer inputs, and irrigation have all served to prevent global food scarcity until now. The key question in this chapter is whether novel techniques in agriculture will be able to keep pace with the growing demand for food in the coming decades. We will also describe a selection of techniques that are considered to be most promising.

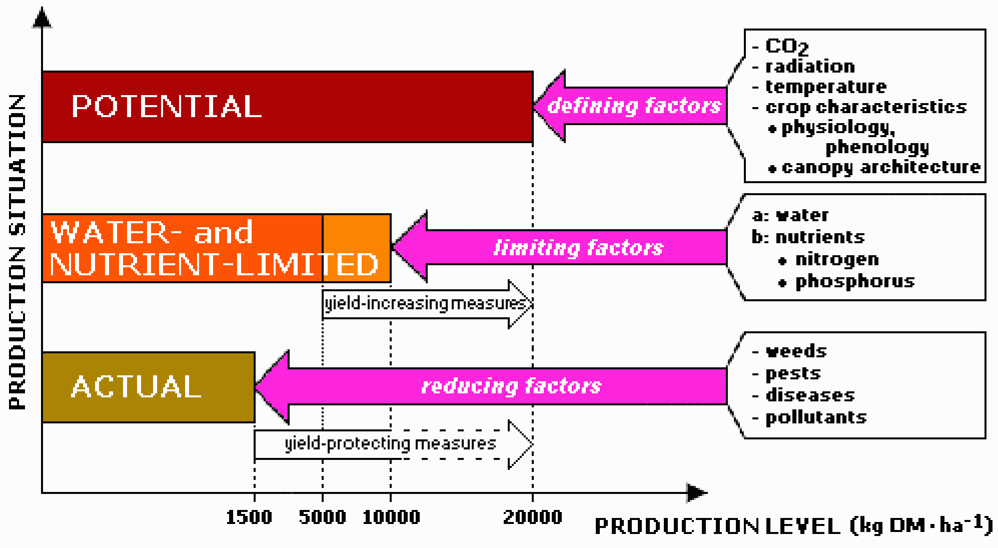
In this section, we will discuss on-farm crop production efficiency. These techniques can be subdivided into three groups according to Van Ittersum & Rabbinge (1997) (see Figure 3 below).

- Techniques that are able to lift the *potential yield*. Potential yields are realized when the crop is amply supplied with water and nutrients, and is free from weeds, pests and diseases. Its growth rate depends only on the current state of the crop and the current radiation and temperature conditions. The potential yield is the uppermost bar in Figure 3.
- Techniques that are able to lift the *attainable yield,* or yield-increasing techniques. The attainable yield is realized when growth rates are limited by water shortage or nutrient shortages for at least one part of the growing season.
- Techniques that improve *actual yields,* or yield-protection techniques. Actual yield are attainable yields reduced by the occurrence of diseases, insect pests, weeds and pollutants.

It is likely that an increase in the potential yield of a crop will also cause an increase in the attainable and the actual yields.

Figure 3

Schematic overview of production situations with indicative dry-matter yield levels for Dutch conditions



(Source: LÖVENSTEIN, H.; LANTINGA, E.A.; RABBINGE, R.; VAN KEULEN, H. 1995 "Principles of production ecology: text for course F300-001". - Wageningen: Department of Theoretical production ecology, Wageningen Agricultural University, 1995. - 121 p. - p. 8, Figure 1.2. (adapted))

Lifting the potential yield: Breaking through the productivity ceiling

To avoid major food shortages in the coming decades, yield potentials of the major cereal crops have to be raised and the existing yield gaps have to be closed (Tilman et al 2002). However, statistical research shows that currently potential yields are not limiting crop growth (Hafner, 2003). This is remarkable because in the last 25 years, the potential yields of rice and maize have not increased (Tilman et al, 2002; Duvick & Cassman 1999). Furthermore, overall performance of agricultural research has decreased (Ruttan, 2002). The efficiency of achieving gains in average maize yields in relation to the amount of investment in maize breeding has decreased by 75% during the past 30 years (Duvick & Cassman, 1999). According to Cassman et al (2003) current trends indicate that lifting yield potential is a difficult scientific challenge, which has been demonstrated as being an unattainable objective (Cassman et al 2003).

Potential yields could be increased in two ways. First, by augmenting the amount of the basic necessities for photosynthesis, these being light and carbon dioxide available for the crop. The second option is to transform the characteristics of the crop, so it will make a better use of incoming radiation and CO_2. Since increasing radiation and CO_2, and regulating temperature can only be done in greenhouses, scientists are bound to change crop characteristics. In this chapter, three techniques are described that can produce future crops that are more light-efficient.

Theoretically, plants could make better use of the sun. The energy contained in a mature crop represents only a small fraction of incident radiation received (less than 5 %) (Reynolds, 2000). Present wheat crops produce 1.2 grams of above-ground biomass from a Mega Joule of absorbed radiation, while theoretical studies indicate that this can be raised to between 1.5 and 2.6. Radiation Use efficiency (RUE) does not appear to have been improved significantly by the plant breeding activities in the past. Even plant breeding actions directed at improving RUE have not yielded significant results (Reynolds, 1999). This is worrying, because attaining an improvement in light-use efficiency is the only way to achieve an increase in future yields, since the harvest index of modern cultivars are approaching the theoretical limit of 60% (Austin 1980). However, according to Reynolds et al (2005) Austin's figure is a rather optimistic one.

Genetic modification of crops to augment crop photosynthesises capacity seems to be a promising approach to improving the use of the sun. Photosynthesis capacity is a function of supply, the photosynthesis itself, and the capacity of the crop to store the assimilates in useful products (sink strength). Means for improving RUE in the field are modifications to the photosynthetic metabolism; canopy architecture; improvements in grain number and size; vascular transport of water, nutrients and assimilates; respiratory costs; and buffering of these processes to environmental fluctuations. In this section, only modifications of the photosynthetic metabolism will be discussed.

Research efforts after enhancing the photosynthetic metabolism have been undertaken in three directions. A) By transforming C_3-crops to C_4-crops (Sheehy, 1999 among others); B) By bringing in improved forms of *rubisco*, the key enzyme for photosynthesis (Mann, 1999); C) by introducing the gene for producing *threhalose*

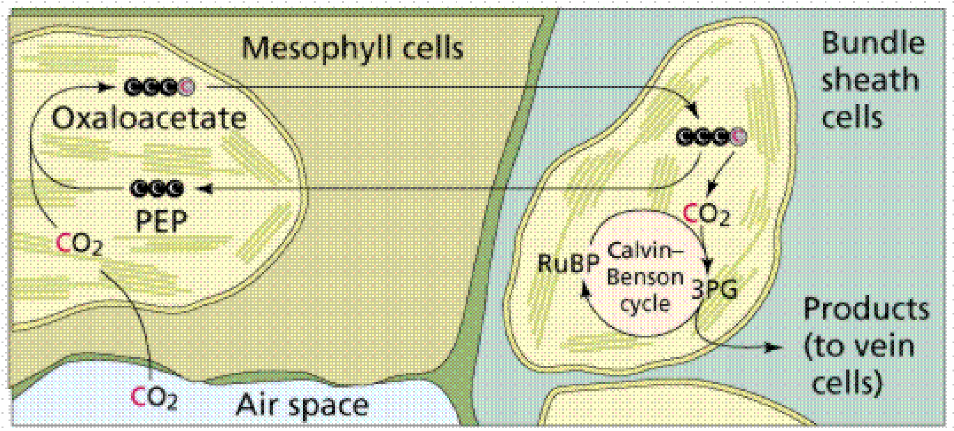
(Garg et al, 2002). We will describe these techniques in more detail here. For the first technique we will focus on rice. Global production of rice, the world's most important staple crop, has risen threefold over the past three decades. Extrapolating this trend, there will be enough food to meet the rising demand. However, world rice yields are moving quickly to the theoretical limit set by rice light-use efficiency. To make a further increase of rice production possible, rice will have to be re-engineered at the biochemical level (Brookes and Barfoot, 2003)

Lifting potential yield technique 1: Transforming C_3-crops to C_4-crops

During photosynthesis, light energy has been converted into chemical energy stored in ATP and NADPH. After that, carbon fixation can take place. Carbon fixation in plants is the method by which carbon dioxide is first built into a sugar. Most plants like wheat and rice are C_3-plants, meaning they fix carbon dioxide first into a 3-carbon sugar, *hosphoglyceraldehyde*, facilitated by *rubisco*. *Rubisco* is the common name of *ribulose-1,5-bisphosphate carboxylase/oxygenase*. This step occurs directly as the first step of the Calvin cycle, not as a separate carbon fixation reaction.

The carbon fixation reactions can occur via two other pathways. The fixation occurs before the Calvin cycle and the products are passed into that cycle. These pathways are favored in many desert plants, because they allow the plants to close some of their stomata, the pores that allow air in, and work with less CO_2. By closing the stomata on sunny days, the plant can keep more of its moisture in, while still performing photosynthesis. Plants using these pathways fix carbon into a sugar then pass that sugar into the Calvin cycle where it is converted to glucose. C_4-plants convert CO_2 into *oxaloacetate*, a 4-carbon sugar using the enzyme *phosphoenolpyruvate carboxylase* (PEPC). CAM plants perform the Calvin cycle at night, when they can open their pores to CO_2 and not risk moisture loss. They pass a 4-carbon sugar malate into the Calvin cycle.

Figure 4: A C_4-plant. Carbon bound and carried by PEP to the Calvin cycle. In C_3-plants atmospherical CO_2 is bound during the Calvin cycle.



Source: Wikipedia

When oxygen levels are high – for example, when the stomata (the tiny pores on the underside of the leaf) are closed to prevent water loss or at high assimilation rates –*rubisco* might use oxygen instead of CO_2. Then it will produce the inutile *glycolate* instead of phosphoglyceraldehyde. This process is called photorespiration. PEPC, the enzyme that C_4-plants use, is more specific for CO_2 then rubisco. C_4-plants, therefore, show less photorespiration, which is schematically shown in Figure 5.

The majority of terrestrial plants, including many important crops such as rice, wheat, soybean and potato, are classified as C_3-plants. C_4-plants such as maize and sugarcane evolved from C_3-plants, acquiring the C_4-photosynthetic pathway to achieve high photosynthetic performance and high water- and nitrogen-use efficiencies.

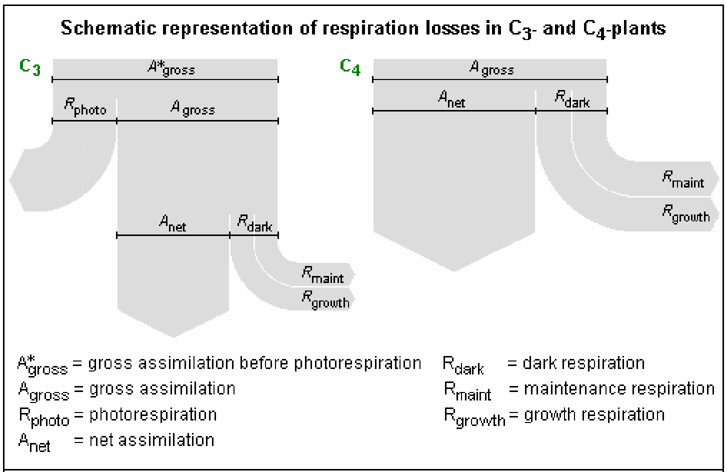
Transformation of rice towards a crop that shows C_4 behaviour can result in a major production increase. This process, however, might not be that easy. C_4-plants often use two types of cells for their photosynthesis, resulting in a different anatomy, called Kranz anatomy. Turning rice into a C_4-plant would therefore imply major changes in rice biochemistry and anatomy. The rice has to be altered in a number of ways; it is not just a matter of plugging in some more advanced enzyme genes.

A research team led by Maurice Ku (1999), succeeded in introducing the maize gene for PEPC and two other enzymes for PPDK, which play a role in C_4 photosynthesis into rice cultivars. Rice plants expressing those maize genes have double the photosynthetic capacity of normal rice. In small-scale field trials in China and South America, up to 90% more grains have been produced. "These plants are also more vigorous and uniform, more tolerant to stress conditions, and flower four to six days earlier than no transformed controls," claimed Ku in Nature (Ku et al, 1999). Agarie et al (2002) did more or less the same and observed a strongly reduced photorespiration, independent of oxygen levels.

But most experts urge caution, because the gains seen by Ku and his colleagues may actually have little to do with the acquisition of C_4-photosynthesis – instead, they might be a result of improved stress tolerance. The production of PEPC can increase dramatically in normal rice plants grown under stressful conditions. And the most spectacular gains in yield seen in the field trials came in plants grown in the stressful environment of

South American soils, which have a high salt concentration and where ultraviolet wavelengths make up a significant proportion of the sunlight. (Surridge, 2002) Furthermore, attempts by Chi et al. (2004) to improve photosynthetic activity by expressing sorghum genes failed.

Figure 5: representation of respiration losses



(Source: IVENS, W.P.M.F. ; *et al.* 1992 "World food production : textbook 2 : biophysical factors in agricultural production". - Heerlen : Open universiteit, 1992. - 247 p. – p.20, fig.1.9)

The question remains as to whether it is possible to create an efficient CO_2-concentrating mechanism in a plant without the special leaf anatomy. Nature provides some good examples of higher plant CO_2-concentrating mechanisms without Kranz anatomy, namely, the submersed aquatic macrophytes (SAMs) such as *Hydrilla Verticillata. Hydrilla* has another special characteristic. When submerged, it uses C_3-photosynthesis, and when floating it uses C_4-photosynthesis (Casati et al, 2000). Genes of this plant can be used to introduce 'single cell' C_4-processes into rice (Leegood 2002). During a modelling exercise, Caemmerrer (2003) discovered that C_4-photosynthesis in a single C_3-cell would be theoretically inefficient due to the absence of the appropriate C_4-infrastructure. On the other hand, it will ameliorate the CO_2 diffusion of C_3-leaves.

Most authors think that turning rice into a C_4-plant will take 10 to 20 years (Bowes et al, 2002; Surridge, 2002), while other experts like Van Keulen are rather sceptical. C_4 rice will be 10 to 35% more productive then C_3 rice (Brookes and Barfoot, 2003) or 25% percent according to IRRI experts (Sheehy, 1999). As C_4-crops are only more efficient in warm climates, engineering C_4 assimilation into C_3-crops will be beneficial only when temperatures are high enough (28 degrees Celsius and higher during the growing season) and when light intensities are high (Mann, 1999).

Lifting potential yield technique 2: More efficient rubisco
Richard C. Leegood (2001) thinks that this will be easier to use a different approach to reduce photorespiration than transforming C_3-plant to C_4-plants. An alternative strategy for improving RUE would be to enhance photosynthetic capacity in C_3-plants by introducing improved forms of *rubisco* in C_3-crops. *Rodophyte algue rubisco,* for example, expresses a higher specifity for CO_2 compared with O_2, causing less photorespiratory losses (Leegood, 2001; Reynolds et al, 1999). Up till now, few results have been published about introducing *rubisco*.

Simulations by Zhu et al (2004) suggest that a very substantial increase (> 25%) in crop carbon production could be achieved when more efficient *rubisco* varieties are trans-genetically introduced in C_3-crops (Zhu et al, 2004; Agarie et al, 2002). Contrary to the C_4-mechanism, crops expressing highly specific *rubisco* will also be more efficient in colder areas. This also makes this technique suitable for crops of the temperate regions like wheat (Reynolds et al, 1999).

Lifting potential yield technique 3: Introduction of trehalose
Garg et al (2002) succeeded in introducing the genes for the production of *trehalose* in rice. *Threhalose* is a sugar-like chemical that bacteria and some fungi use in order to survive during a lengthy period of harsh conditions. Rice cultivars expressing the chemical are more resistant to drought and salinity (see section on limiting factors). Besides that, transgenic plants show a 5 to 15 percent increase in photosynthetic activity, probably due to reduced photorespiration (Garg et al, 2002).

Conclusion
Three techniques were described that can improve the photosynthetic capacity of crops. Research on these techniques is still in progress, but the preliminary results are promising enough to expect that potential yields of transgenic crops with improved light-use efficiency will grow by 10-20 percent in the coming decades. CGIAR institutes host or sponsor most of the research. As the budgets of those institutions are decreasing, the development of these high potential transgenic crops might be at risk.

Lifting the attainable yield: Yield-increasing techniques

Yield-increasing measures are taken to overcome the shortage of water or nutrients during one or more stages of crop development, to lift the attainable yield. The simplest measures are, of course, irrigation and fertilisation. However, world water reserves are under great pressure (see Chapter 4) and world fertilizer use is increasing sharply, which has a serious effect on the environment. Nowadays, farmers use 64 times more artificial fertilizers than in 1930 and this figure is expected to double in 2025 and triple in 2050 (see Table 1). This may not happen without serious damage being done to the environment (Vitousek et al., 1997). Nitrogen is nowadays not used more efficiently than it was 50 years ago (Dobermann, 2000) and although not everyone agrees (Hafner, 2003b), responses to nutrient gifts seem to have entered the phase of diminishing returns (Dobermann & Cassman, 2002; Tilman et al, 2002; Nijland & Schouls, 1997). Energy use of nitrogen fertilizer by agriculture is significant. In 2000, agricultural nitrogen use was responsible for one percent of world marketed energy use and three percent as expressed of world oil production in 2004. In 2025 these figures might rise to 7% of world oil production in 2004 and to 10% in 2050 (Table 1). Nutrient-use efficiencies can be increased by genetic improvement of crops, improved tillage operations, more precise nutrient gifts, and by improved pest and disease management. Whether nutrient-use efficiency is higher at lower nutrient gifts than at higher nutrient gifts is still the subject of an ongoing debate (see Box 3).

This subsection will explore some findings that might improve attainable yields. First, we will discuss the development of a new rice variety, which promises to grow better with fewer inputs than other varieties. Second, two examples are given of biotechnological solutions that can make rice cultivars more drought-resistant. Third, three innovations that are related to soil management are discussed briefly: zero or minimum tillage, the beneficial effect of N-fixing soil bacteria, and precision agriculture.

Table 1: Energy requirement of fertilizer use in agriculture

Year	**1930**	**1960**	**2000**	**2025**	**2050**
N fertilizer use Millions of Metric Tons	1.3[1]	10.2[1]	85[1]	168[3]	240[2]
Energy requirement in billion Mega Joule [7]	85	663	5525	10911	15600
Energy requirement expressed in millions of barrels of crude oil[4]	14	108	903	1783	2549
Energy requirement expressed as percentage oil production 2004[5]	0%	0%	3%	7%	10%
percentage of marketed energy consumption 2003 [6]	0%	0%	1%	2%	4%

1. Source: Frink et al. (1999)
2. Source: Tilman (1999) Number is calculated assuming a doubling of food production in 2050 in combination with a linear extrapolation of N requirement used for augmenting production
3. Source: Prospect based on calculation following calculation. N fertilizer need 2025 N = fertilizer need 2000 (see table, Frink et al, 2005) + increase in N fertilizer need. Increase in N fertilizer need = increase in cereal production (estimated 60 %) * N in grain (rice)(0.018 kg/kg (Datta, 1981) * recovery efficiency (0.3 N uptake (kg) / applied N (kg) (Cassmann & Dobermann, 2002)).
4. Energy content of one barrel oil equal 6,119 Mega Joule. (EIA, 2005)
5. The world oil production per year in 2004 equals 26,5 billion barrels (EIA, 2005b)
6. The marketed total Energy consumption in 2003 equals 4.4 hundred thousand billion Mega Joule (EIA,2005c)
7. Energy requirement for 1 kg N in inorganic fertilizer equals 65 Mega Joule (McLaughlin, 2000)

New Rice for Africa

In Africa, rice production levels are low compared to Asia. High-producing Asian rice varieties do not produce satisfactory yields in Africa due to a lack of fertilization and irrigation. Traditional African rice is rather persistent, but produces only small yields because of its low harvest index. Scientists at the African Rice centre, WARDA, succeeded in developing more than 3,000 progenies of site-specific hybrid rice by crossing a variety of *Oryza sativa* (common name: Asian rice) and a line of *Oryza glaberrima* (African rice). The hybrid rice was given the name of NERICA (New Rice for Africa). In field trials in West Africa, the hybrid yielded 35% more than African rice. The panicles of NERICA hold up to 400 grains compared to the 75-100 grains of its African parents, and can potentially double the production of rice. NERICA matures 30-50 days earlier than traditional varieties, allowing farmers to grow extra crops of vegetables or legumes. NERICA grows better with little input such as fertilizer or irrigation than Asian Rice (Ho, 2004).

WARDA scientist think that around 2010 some 200,000 ha will be under NERICA, which will cause an increase in production of about half a million tonnes (assuming a current production of 2 tonnes/ha, which is

3% of the entire rice production of Africa. There are no independent figures available about the current rate of adoption of the NERICA, nor about its on-farm performance. (Inter Academy Council, 2004; WARDA, 2005)

Biotechnological techniques to increase nutrient-use efficiency

Andrews et al (2004) and Good et al (2004) found that N-use efficiency and crop yield can only be improved by genetic engineering by i) improving nitrate assimilation in roots and shoots or (ii) by introducing an enzyme (GS1) that improves the transport of nitrogen from the leaves to the grain. The first method is only effective under cold or poor conditions, and the latter makes sense for rice only (Andrews et al. 2004). However, Britto & Kronzucker (2004) argue that, based on model outcomes, acquiring maximum N-use efficiency requires overexpression of three enzymes (PEPcase, PPDK and GS). Overexpressing three enzymes can be considered an extremely complicated research effort. It is uncertain whether any of these efforts will have measurable impact on increasing rice yields in the near future. (Dobermann et al, 2002).

Biotechnological techniques to increase drought resistance in rice

Babu (2003) marked the chromosome region in rice that might be responsible for drought resistance in rice. These types of marking projects facilitate breeding for drought resistance. Experts expect that rapid progress in drought resistance will be possible in the near future, due to recently available gene marking, and engineering techniques. (Datta, 2003; Chaves and Oliveira, 2004).

Grag (2002) succeeded in engineering a rice variety that can withstand a long period of drought. Grag's research team introduced a *threhalose*-producing gene into rice. *Trehalose* is a simple sugar that is produced naturally in a wide variety of organisms – from bacteria and yeasts to fungi, including mushrooms – and in many invertebrates, particularly insects. Normally, there is not much *trehalose* in plants, with the exception of the so-called resurrection plants that can survive prolonged droughts in the desert. Drought-stressed resurrection plants look like they are dead and gone forever; then they pop back to life when moisture is available. At the cellular level in plants, *trehalose* helps maintain individual cell structure and function during severe environmental stresses that would kill most plants. The sugar appears to help plant cells regain function and efficiency when stress is no longer present. Several years of research-and-development work, safety testing and certification are needed before large-scale production and distribution of transgenic rice seeds to farmers can begin. Chaves and Oliveira (2004) describe eight other projects that focus on increasing the resilience of rice during dry periods.

Zero or minimum tillage

Zero or minimum tillage implies fewer or no tillage operations. Weeds are removed manually or through pesticides, and seeding and harvesting are done with as little soil movement as possible. The clearest advantage of zero tillage is reduced labour cost. Furthermore, it can increase soil organic matter and improve the hydrological properties of the soil. Improved moisture retention of the non-tilled field was responsible for higher yield under no-tillage than under conventional tillage in experiments done by Gregory et al. (2005). Overall effects on yields appear to be small but no tillage techniques seem to be able to increase nutrient and fuel use by agriculture. (Hernanz, 2002; Kaval, 2004).

Plant growth stimulating micro-organisms in the root zone

Microbial life flourishes around the roots of a plant. This zone, which is also called *rhizosphere,* is relatively rich in nutrients. These microbes are beneficial, harmful or neutral. Beneficial bacteria that support plant growth are usually called plant-growth-promoting *rhizobacteria,* or PGPR. Only free-living bacteria, which do not live in symbiosis with plants, are called PGPR. Therefore, *rhizobia* in symbiosis with legumes are not called PGPR, because they are not free-living. Both *rhizobia* and PGPR are able to fix atmospherical N_2 and are therefore called *diazotrophs*. However, the symbiotic N_2-fixation is more effective by far (3-206 kg N ha-1 yr-1 for grain legumes) than the fixation by free-living micro-organisms (less than 5 kg N ha-1 yr-1) (Giller, 2001). Some non-symbiotic *diazotrophic* bacteria live around the roots, while others live inside the roots themselves. (Bashan et al, 2004).

Although symbiotic rhizobia look more promising in terms of N-fixation, this study focuses on the non-symbiotic bacteria. Currently, much research is being conducted into these diazotrophs, especially *Azospirillum spp*, because of their more general plant-growth stimulating characteristics.

Free-living *diazotrophs* can affect plant growth directly by fixing atmospherical N_2. Researchers discovered that the nitrogen fixation is not the main reason for the observed growth stimulation (Dobbelaere et al, 2003; Bashan et al, 2004). Although it might be important in the long term, other factors are considered more important. These factors include synthesis of root-growth stimulating hormones and vitamins, improved nutrient uptake, enhanced stress resistance, solubilisation of inorganic phosphate, and mineralisation of organic phosphate. Indirectly, *diazotrophs* are able to decrease or prevent the deleterious effects of pathogenic micro-organisms, mostly through the synthesis of antibiotics and/or fungicidal compounds, through competition for nutrients or by the induction of systemic resistance to pathogens. In addition, they can affect the plant indirectly by interacting with other beneficial micro-organisms. The benefits are especially clear in marginal areas (Matiru and Dakora, 2003; Dobbelaere et al, 2003; Bashan et al, 2003; Welbaum et al, 2003).

Although, much research has been done into *diazotrophs*, the processes involved are still poorly understood. (Giller and Merkx, 2003; Matiru and Dakora, 2003; Bornman, 2004). The best-researched and most promising PGPR is *Azospirillum*. However, in field trials with a single inoculation of these bacteria, no consistent yield response was found, although scientists using *Azospirillum* inoculated together with other micro-organisms in field experiments did find a significant rise in yields. Over a hundred crops are reported to respond positively to inoculation with *Azospirillum* (Bashan et al, 2004).

Scientists have been trying to boost nitrogen fixation by genetic manipulation of *Azospirillum*. However, a genetically manipulated bacterium that provides plenty of nitrogen to the plant without compromising its fitness is still a long way from being developed (Bourget, 2004).

Diazotrophic bacteria living inside the roots of agricultural crops are considered to be more promising in terms of nitrogen fixation. In Brazil, the long-term continuous cultivation of sugarcane with low N fertiliser inputs, without apparent depletion of soil-N reserves, triggered scientists to search for N-binding bacteria on the crops. Results from N balance and N-15 experiments showed that some Brazilian varieties of sugarcane were able to obtain large amounts of N from these bacteria (Zahir et al, 2003; Raven et al, 2005). However, Giller (2003) doubts the correctness of the research methods and argues that evidence for a large contribution from N_2-fixation by *diazotrophic* bacteria is weak, although sugarcane is the crop that can benefit most from *diazotrophic* bacteria because of the high carbon content in the root zone of the crop.

Several *diazotrophs* that have infected the interior of the plants have been found, including *Gluconacetobacter diazotrophicus*, *Herbaspirillum seropedicae*, *H. rubrisubalbicans* and *Burkholderia sp*. Work has continued on these bacteria within sugarcane plants, but it is still not known which of the bacteria causes the fixation and in what site, or sites, within the cane plants the N_2-fixation mainly occurs. Until such important questions have been answered, further developments or an extension of this novel N_2-fixing system to other economically important non-legumes (e.g. cereals) will be seriously hindered.

There are strong indications that the presence of *Azospirillum* played an important role in the development of the so-called black Indian soils of the Amazon (*terra preta do indios*) that once fed significant populations in what is nowadays called the `untouched' rainforest (German, 2002; Heckenberger, 2003; Wirtz and Lemmen, 2003; Lehman et al, 2004). Whereas the natural soils of the Amazon provide harsh conditions for beneficial microbes (low pH, high Al), the anthroposols provide the optimum conditions for *diazotrophic* bacteria. As a result, *Azospirillum* is hard to find in ferralsols but abundant in the black Indian soils. Although, it is still not clear what came first, the suitable conditions or the bacteria, a more co-evolutionary development is not unlikely.

The cost of developing novel inoculant materials is currently too expensive for the agriculture sector, especially in developing countries. There is some hope that a wider use of encapsulated micro-organisms in non-agricultural applications may help these materials become cost-competitive in agriculture as well, which is currently not the case (Bashan et al, 2004).

It can be concluded that the advantage for agriculture probably does not lie in the nitrogen fixation capabilities of *diazotrophic* bacteria. Nevertheless, if production costs of inoculant bacteria decrease, the technique might be able to improve yields significantly, especially in less suitable areas. Yield increases in high-input farming systems are less probable.

Precision agriculture

Precision agriculture is one of the technologies mentioned by the expert group that might be able to propel farm biomass production into the future. Precision agriculture can be defined as a holistic management strategy that uses information technology to bring data from multiple sources to bear on decisions associated with agricultural production, marketing, finance, and personnel (Hernanz et al, 2002).

Precision agriculture was initiated in the mid-1980s, using newly available technologies, to improve the application of fertilizers by varying rates and blends as needed within fields. The concept has been adapted for a variety of practices, crops, and countries. Its adoption varies significantly per cropping system, region, and country but it has been progressively introduced or evaluated around the world. Precision agriculture is relatively popular in rich countries because it is seen as a tool to diminish the emissions of N, P and toxic chemicals from agriculture.

Several types of challenges limit a broader adoption: socio-economic, agronomic, and technological. Socio-economic barriers are the principal high cost and the lack of skills. Agronomical challenges are the lack of basic information, inadequate sampling and scouting procedures, absence of site-specific fertilizer recommendations, misuse of information, and lack of qualified agronomic services. There are multiple technological barriers that relate to machinery, sensor, GPS, software, and remote sensing.

Roberts (2002) thinks that these barriers will be progressively lifted, and that precision agriculture will become a significant component of the agricultural system of the future. Dobermann & Cassman (2002) studied nutrient efficiency both in rice systems in Asia and in corn systems in the USA. They concluded that a more precise, spatial-specific nutrient management is needed in order to close the yield gap in these agricultural systems. Dobermann et al (2002) found that site-specific nutrient management can increase yields by seven percent while decreasing nitrogen amounts, wheras currently the average nitrogen recovery efficiency is only .3 kg/kg (supplied N/harvested N) for rice and .37 kg/kg for maize. Recovery efficiencies of 50 to 80% can be achieved in field experiments with good management.(Dobermann & Cassman 2002). However, recent modelling outcomes of a research team led by IRRI scientist Sheehy (2005) show that under the most precise nutrient management, the maximum recovery efficiency is only 57 %. These outcomes show that the hypothesis that fertilizer nitrogen losses from high-yielding irrigated rice could be almost eliminated by delivering the precise amounts of nitrogen required to support growth at any given time might be false. As 57 % is still twice as efficient as currently being achieved, precision agriculture could significantly diminish nitrogen losses. However, while economically promising in the longer term, it is expensive relative to the incomes of most farmers in Asia, except for Japan. (Shibusawa, 2000; Dobermann & Cassman, 2002). The chief challenge for site-specific nutrient management is to reduce its complexity. The method should be adapted to specific situations in different areas. In some areas, site-specific management can be field- or farm-specific, but in many areas it is likely to be just region- and season-specific (Dobermann et al, 2002). Additionally, Gandah et al (2000) found that visual scoring techniques are very suitable for measuring spatial variation in nutrient levels. This is thought to be a promising technique for resource-poor farmers (Goma et al, 2001; Voortman et al, 2004).

If the adoption of precision farming increases in the coming decades in high-mechanized maize and wheat systems, as Robert (2002) expects, it will increase productivity significantly. Rice production is not likely to be affected by these developments, as the techniques will be too expensive or complex for rice farmers. Too little is known about the possible impact of visual scoring techniques, for anything to be said about the possible impact on food production in the future.

Concluding remarks

Precision farming might increase both agricultural productivity and nutrient efficiency in the richer parts of the world. Growth-stimulating bacteria will be of use in the less suitable areas, if the cost of inoculation decreases. Zero tillage is unlikely to affect global food production, although it might increase sustainability. Both conventional and biotechnological breeding efforts can produce crops suitable for marginal areas, like New Rice for Africa (NERICA) and drought-resistant transgenic varieties. Intensive rice farming systems in Asia are not expected to benefit much from any of the techniques described. In order to reach the maximum attainable yield, farmers will still have to call upon their friends from the green revolution: artificial fertilizer and irrigation.

Box 3: The debate on nutrient efficiency

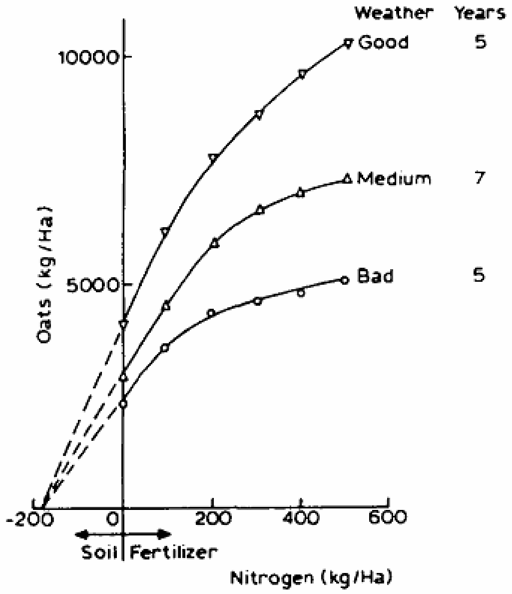
Liebscher: one theory, two views

Is a crop more nutrient-efficient at high nutrient levels or at low nutrient levels? The former view is that of a large group of Wageningen agronomists doing research with the paradigm of C.T. de Wit. De Wit (1992) found that where nutrients are applied in optimal proportions, nutrient-use efficiency will increase when nutrient gifts are increased. A small group of scientists, most of them with roots in organic agriculture, oppose this concept. According to them there is no optimal proportion of nutrients other than the lowest (Nijland & Schouls, 1997).

Although these views seem rather opposing, both Nijland & Schouls and de Wit base their visions on Liebscher's law of the optimum (1895). 'The closer other production factors (like nutrients and water, editor's note) are to their optimum, the better plants can use a production factor in minimum supply in order to reach a higher production' (translation by Zoebl, 1996). De Wit (1992) re-formulated the law as follows: 'A production factor that is minimum in supply contributes more to production the closer other production factors are to their optimum'. Nijland & Schouls (1997) state: 'The interaction between inputs increases when the availability levels increase, up to a certain amount. Beyond that, the interaction decreases again. So the activity of a limiting nutrient is more pronounced as the other nutrients are closer to the optimum.' From here views diverge strongly.

De Wit continues and concludes from Liebscher's law combined with experimental data, that all production factors are most efficiently used when they are all at their optimum. De Wit validated his theory with examples such as those shown in Figure 6 which shows the results of an experiment in Denmark on the response of oats to nitrogen fertilizer during 1924 and 1940 in years with relatively good, medium and bad weather. The increased response to nitrogen under better weather conditions did not only manifest itself at high rates of application, but also when nitrogen was in short supply (de Wit, 1992).

Figure 6: Average nitrogen response curves of wheat for years with relatively good, medium and bad weather for 1925-1940 (Nielsen, 1963)



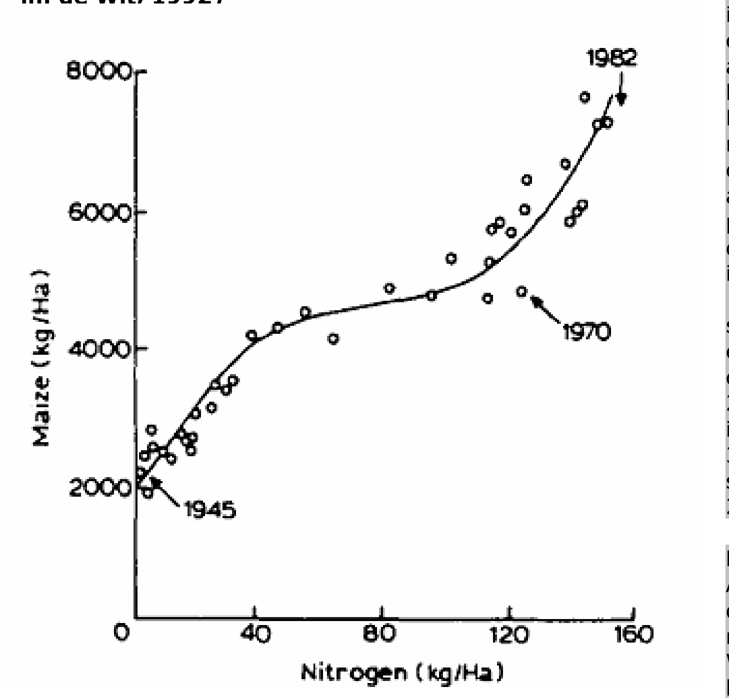
Nijland & Schouls agree with the validity of Liebscher but propose that there is no optimum nutrient gift and that marginal returns will be decreasing rather increasing at high nutrient levels. They used the Michaelis-Menten model for mathematically representing Liebscher's law. The Michaelis-Menten equation is an hyperbolic function. The model may be written as follows:

$$\frac{1}{Y} = \frac{1}{MY} + \frac{1}{\alpha \cdot N} + \frac{1}{\beta \cdot P} + \frac{1}{\tau \cdot K}$$

In which Yield (Y) is a function of maximum yield (MY) (kg dry matter/hectare), Nitrogen, Phosphorus, and Potassium availability (N,P,K in kg/ha) and the coefficients of response of production to the availability of the respective nutrients (α, β, τ).

Nijland & Schouls tested the validity of this model on data from different publications; partly the same as C.T. de Wit used. They tested Michealis-Menten, for example, on Nielsen's oat experiment (Figure 6) and

Figure 7: Maize yield versus nitrogen fertilizer rate in the USA during the period 1945-1982 (Sinclair, 1990 in: de Wit, 1992)



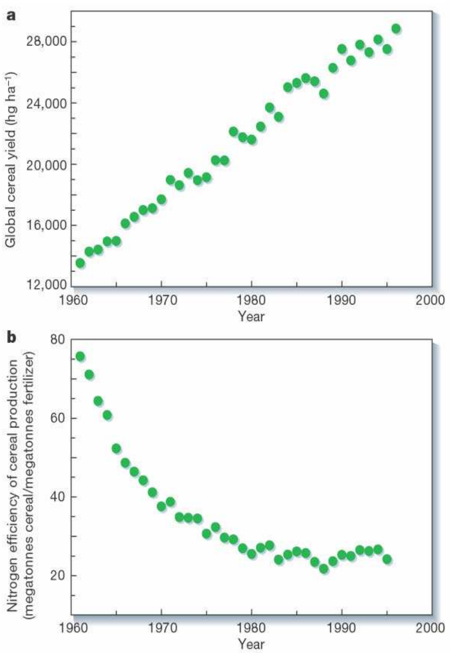
concluded that these data gave support for the Michaelis-Menten Model. They found the Michaelis-Menten model an appropriate representation of Liebscher's law. From this they conclude then that if Liebscher's theory is applicable, it follows that no optimal level of nutrient availability for proportionally available nutrients exists, other than the lowest. This is due to the special feature of Michealis-Menten that, along the whole nutrient availability range, the productivity of one nutrient rises as another nutrient availability is increased, whilst the productivity of the other nutrient itself decreases as the latter nutrient availability increases.

Nijland & Schouls' proposition is supported by results from a 21-year experiment comparing organic and conventional farming methods (Mäder et al., 2002). These results indicate that nutrient input (N, P, K) in the organic systems were 34 to 51% lower than in the conventional systems, whereas mean crop yield was only 20%.

Homogeneity trap

According to Nijland & Schouls (1997) the difference between de Wit's conceptual model and theirs is a matter of scale. de Wit's concept might be true in small homogeneous research plots, but in the real world, temporal and spatial variations will diminish the effect of the positive interaction between nutrients and cause diminishing returns. The hypothesis that the aggregation level is responsible for the different paradigms is supported by earlier findings of Noordwijk & Wadman, (1992) and Nijland (1994) who showed that spatial variability leads to higher 'economic optimum' gifts.

Figure 8: (a) Trends in average global cereal yields; (b) trends in the nitrogen-fertilization efficiency of crop production (annual global cereal production divided by annual global application of nitrogen fertilizer) (Tilman et al., 2002)



Roetter et al. (2000) showed the validity of de Wit's version of the law of the optimum using the results of research performed by a research team led by Dobermann (2000) and Peng (1996). Dobermann's team looked at the causes of the yield incline of IRRI's experimental plots between 1991 and 1995, which followed a small decline of yields between 1965 and 1991. They found that reducing preplant N fertilizer and increasing the number of split applications had a greater effect on increasing yield than the increase in the amount of N applied. These findings, however, do not necessarily provide evidence for de Wit's theorem. On the contrary, as Dobermann shows that the low yields and nutrient efficiencies were caused by heterogeneity of N application in time and not by the absolute N gifts, these results support the proposition of Nijland & Schouls rather than that of de Wit. The same applies for the results of Peng (1996). The team led by Peng (1996) yielded more rice under high fertilization levels and constant monitoring and adjustment of N gifts on research plots of IRRI and the national rice research institute of the Philippines. So again productivity was increased by increasing temporal homogeneity on rather homogeneous research plots.

The debate is made more difficult by the fact that both Roetter et al (2000) and de Wit (1992) tangle the effects of technological innovations, like split application and real time N measurements. For an appropriate evaluation of the validity of the de Wit and Nijland-Schouls theory, the effects of technological innovation should be untangled.

Technological innovation

The graph in Figure 7 above was used by de Wit (1992) to illustrate that there is no decrease in marginal returns. Fertilizer is used just as efficiently at the high end of the yield range as at the low end. According to de Wit, this is due to technological innovation, which has caused a more nutrient-use efficiency to stay stable while production has quadrupled.

This optimism, however, is not shared by Nijland and Schouls (1997). They find it "striking that no real increase in nutrient productivity may be observed." They reanalysed the data and calculated the sustainable system: kg biomass from external + internal nutrients (exclusive mining) per kg applied nutrients, and concluded that the productivity had decreased instead of remaining constant. Nijland & Schouls recently got support from Tilman et al. (2002), who showed diminishing returns in nitrogen gifts (Figure 8).

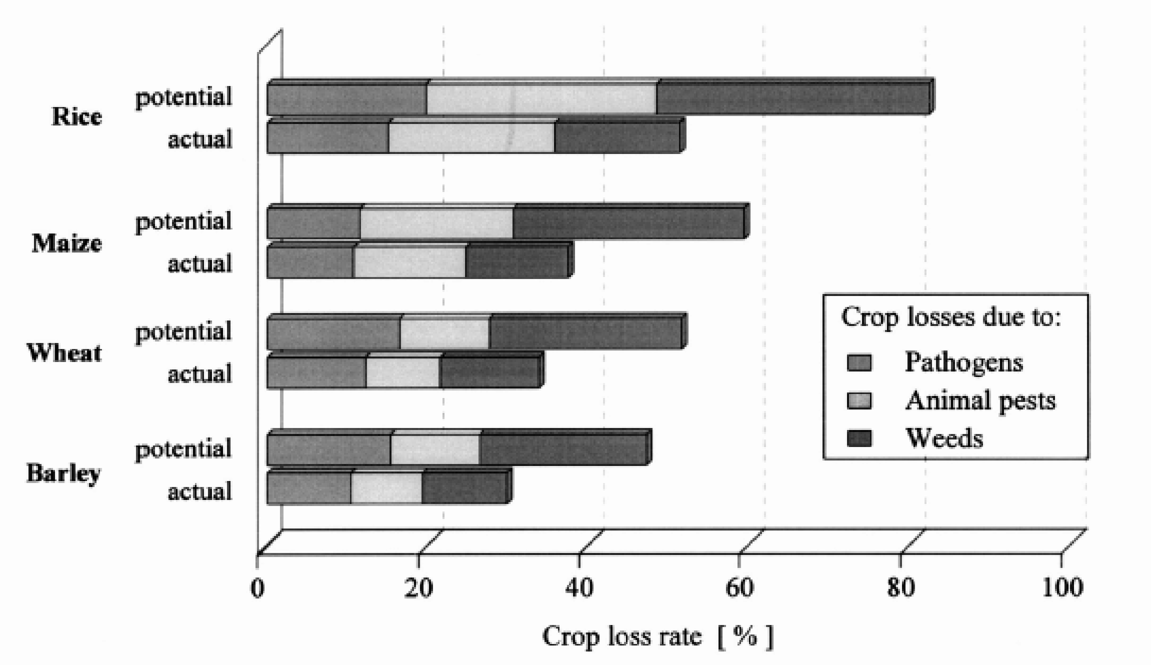
Consequences
In planning the future of agricultural regions, theory does matter. Followers of de Wit (Rabbinge, 1992) and de Wit himself used his theory to defend a European spatial planning in which high productive agriculture takes place on the most suitable soils in order to diminish environmental pollution by nitrogen losses. If the Nijland and Schouls theory is a better representation than that of de Wit, total nutrient emissions will be lower if more land and lower nutrient inputs are used.

Lifting the actual yield: Yield-protecting techniques

As already mentioned, actual crop production is defined as water- and/or nutrient-limited production, which is further reduced by effects of weeds, pests (insects, mites, nematodes, rodents, birds), diseases (fungi, bacteria, viruses) and/or pollutants (especially air pollution).

In spite of intensive crop protection measures, this is the common production situation for the majority of the world's agricultural production systems. In 1994, losses for eight major crops were estimated. On a worldwide scale, these would add up to 40% loss due to insects, diseases and weeds (Oerke, 1995). In this section, we will focus on reducing crop losses due to pathogens, animal pests and weeds by trans-genetic breeding of more resistant crops. We will start with rice, continue with corn (maize) and wheat and end with 'orphan' crops. As we can see in Figure 9, rice is the crop with the highest potential losses (loss without pest and disease management), as well as actual losses.

Figure 9: Crop losses without loss-reducing measures (potential) and actual crop losses (Oerke and Dehne, 1997)



Rice
Rice definitely is the staple food crop on which most biotechnological research is done (Brookes and Barfoot, 2003; Datta, 2003). Table 2 shows an overview of transgenic cultivars and their status of resistance to pest or diseases. Most cultivars are expected to be released between 2005 and 2010. Especially bacterial leaf blight and insect resistance are expected to have big impacts on yields.

Bacterial leaf blight is a major problem for growers. The introduction of the Xa21 gene improved resistance to all races of bacteria leaf blight. This cultivar is expected to be released on the Chinese market in 2006 just like the Bt-cultivar, which shows broad-spectrum resistance against the stem borer. An important drawback of the Bt-varieties is the recent advent of Bt-resistant pests. More information on this is given in the maize section. As described in Section 2.4, the fight against pathogen, weeds and animal pest is an ongoing rat race. New crop protection measures have to be developed as pathogens and pests and weeds become resistant to prevailing fungi, pest and herbicides. It is still uncertain whether transgenic strains will be just another step in this rat race. In other words, will they really improve actual yields or will they be able to lift actual yields durably.

For the five mainstream multinational biotechnology companies, rice has been an important priority crop for research but in recent years, it has been downgraded to a 'second- or third-tier' crop. This largely reflects a perceived limited scope for capturing value through the rice crop and hence a reasonable return on investment. When it comes to forecasting the future availability of transgenic rice, this might lead to two completely divergent situations. On the one hand, multinational companies are not likely to invest much money in rice research, leading to the development of transgenic rice varieties becoming scarce. At the same time, multinationals do not expect to get much money from patents, whereby the (publicly developed) transgenic seeds might become freely available to farmers. (Brookes and Barfoot, 2003; Datta, 2003).

Table 2: Overview of transgenic cultivars and their status of resistance to pest or diseases

	Trait	Cultivar	Remarks
Xa21	Resistance to bacterial leaf blight	IR72, IR64, IR68899B, MH63, BPT5204, Pusa Basmati-1, IR50, CO39	IR72 field-evaluated in China, India, and Phillipines
Bt (cry1Ab, cry1Ac, cry1Ab+cry1Ac), cryIIA	Resistance to insect pests	IR72, IR64, MH63, IRRI-NPT, Vaidehi	IR72 and MH63 field-evaluated Hybrid Bt rice now grown in China
Chitinase (chi11, RC7), tlp D-34	Sheath blight resistance	IR72, IR64, CBII, Swarna	Transgenics showed enhanced protection against fungus
Xa21 + Bt + PR genes	Resistance to bacterial blight, stem borer, and sheath blight	IR72	Transgenics showed broad-spectrum multiple resistance
ORF2[a] for serine protease and RNA-dependent RNA polymerase	Resistance to rice yellow mottle virus	ITA 212 (FARO 35), Bouaké 189, BG90-2	Transgenics showed resistance against low- and high-dose virion and RYMV RNA inocula

Source: Datta (2003), Brookes (2003)

IRRI[1] expects a 30 percent rise in production caused by genetical improvements by the end of 2010. ISAAA[2] expects a 10% increase in production. This difference is largely caused by the fact that ISAAA estimated lower adoption rates than IRRI. ISAAA expects transgenic crops to be accepted and adopted first in China. From there, diffusion will take place to other countries (Brookes and Barfoot, 2003; Datta, 2003).

Although both private and public research into transgenic rice might be decreasing, rice is still the crop that gets relatively much biotechnological attention. In combination with the Chinese willingness to adopt biotech rice cultivars, ISAAA's estimation of a 10 percent increase in rice yield caused by genetic breeding for increased pest resistance in 2010 might be realistic, unless pathogens and pests become resistant too fast.

Zea maize - Insect resistance

14% of the world's area under maize (143 million hectare) is sown with transgenic seeds. 80% of this is so-called Bt-maize, maize variety that has been made resistant to stem borers by introducing a gene from *Bacillus thuringiensis* that produces proteins, which are toxic to insects. Besides Bt-maize, little biotechnological engineering has been done for maize, except for the Roundup-Ready varieties.

There is a relatively long field experience with Bt-maize. Generally, Bt-maize performs well in terms of cost-saving and yield. Brookes (2003) claims a 7% yield increase in Spain through the introduction of Bt-maize. Spain is the only EU-15 member that allows the production of transgenic crops. Till now, no available Bt-variety has proven resistant to African stem borers or moths. CIMMYT[3] is developing an insect-resistant maize variety (Hosington and Ngichabe, 2004). This is a very complex task due to the very complex ecology of the plagues in

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[1] IRRI: International Rice Research Institute

[2] ISAAA: The International Service for the Acquisition of Agri-biotech Applications

[3] CIMMYT: International Maize and Wheat Improvement Center

Africa. Mugo et al (2001) expect that the Kenyan farmer can achieve a15 to 53 percent yield increase using their Bt-Maize that is under development.

Although Bt-resistant stem borers have already been found in Indonesia and India, Bourget (2004) does not expect Bt-resistance to develop in Europe. In order to avoid resistance, an integrated approach is needed in which farmers have to plant non-Bt species within or around their fields. Furthermore, Bt-doses have to be high enough (Caemmerer, 2003). However Chilcutt and Tabashnik (2004) discovered that this strategy is not preventive enough. Pollen can travel long distances, making the Bt-maize mix with non Bt-maize and resulting in plants or organs that show low doses of the toxic, thereby making it easier for the insect to become resistant.

For the Americas and Asia, Bt-maize is not a new phenomenon. An increase in yield through this cultivar will be a matter of adoption. The advent of Bt-resistant insects might even lower future production rates. A Bt-maize for Africa has the potential of increasing yields significantly. As only a small amount of world corn production is grown in Africa, global effects will be marginal.

Wheat

Few efforts have been undertaken to genetically modify wheat. The world's first genetically modified wheat was shelved because of consumer resistance. US agrochemical company Monsanto announced in May 2004 that it would not try to market its Roundup-Ready strain. The company has already engineered the strain to survive its own Roundup brand of weed killer.

Orphan crops

In addition to a small number of well-known major global crops such as maize, rice, and wheat, many more crops are regionally or locally important for nutrition and income in poor regions. Crops such as plantain and bananas; root and tuber crops such as cassava, sweet potato, and yam; millets such as pearl millet, finger millet and foxtail millet; legumes such as quinoa; and many types of vegetables are all critical for food security and nutrition on a regional or local scale. Twenty-five of such 'orphan' crops within developing countries total some 240 million hectares, with an additional 70 million hectares planted to fruits and vegetables. In sub-Saharan Africa, for example, sorghum and pearl millet are more important than rice and wheat, both in area (41 million ha. vs. 9 million ha.) and in contribution to diet. Roots and tubers are essential staples in Africa, where cassava is the third most important source of calories overall. (Morgan et al, 2002; Nelson et al, 2004).

Little research has been done on these crops. To give an illustration: in the western world, only two research institutes perform fundamental research on cassava. Experts like Prof. Richard Visser think that the amount of fundamental research will diminish further in the future. Experts think that using conventional breeding techniques might still be useful for these under-researched orphan crops. However, conventional breeding programmes were not able to cope with major biotic stresses like the witch weed *striga*, which causes 40% production losses for many African sorghum and maize farmers. Some authors believe that biotechnology might provide the solution for these biotic stresses, since agronomical measures are too expensive and labour-intensive. (Bornman, 2004; Kanampiu, 2002).

Gressel et al (2004) describe an approach to fight *striga* by having the crop root emit a toxin. As there is a metabolic cost to constitutively producing toxins, as well as a possibility of autotoxicity, toxics are only released when the crop is under parasite attack. However the experiments are still in a very experimental stage. Gressel et al (2004) further described that hardly any research is being done into the most harmful pest and plagues of Africa.

It can be concluded that due to the lack of research, hardly any progress in terms of yield increase is expected in the coming decades for orphan crops.

Concluding remarks

Rice is the only crop whose actual yields will increase significantly through biotechnological breeding activities. Its yield is expected to increase ten percent by 2010.

Conclusion and discussion

Techniques improving potential, attainable and actual yields were studied. Future transgenic rice cultivars with higher light-use efficiency due to built-in C_4-photosynthesis might, according to experts, be able to improve potential yields by 10-20% in the coming decades. Not all experts share the optimistic view that transgenic crops with improved potential yields will come available within the next 20 years. Crop varieties with improved *rubisco* might increase both rice and C_3-crops growing in temperate regions like wheat.

We did not find much evidence that attainable yields will increase significantly without calling heavily upon artificial fertilizer or more irrigation. Precision farming has the potential to improve yields slightly in the richer parts of the world. Yields in marginal areas can benefit from research into growth-stimulating bacteria in combination with breeding efforts that produce crops that are more drought-resistant. Intensive rice farming systems in Asia are not expected to benefit much from any of the described techniques. On the other hand, actual rice yields in Asia are expected to improve through the relatively large amount of transgenic pathogen or animal pest-resistant transgenic rice varieties that will become available in the near future. A key question is whether these transgenic strains are a long-term solution for diminishing crop losses.

Little research being carried out on the so-called orphan crops as compared to more commercial crops like wheat and potato. Experts do not expect any growth of funding for this type of research, so yields from these crops are expected to remain stable in the coming years. Diminishing contributions of donor countries to the public agricultural research institutes can endanger all the developments described. Virtually all biotechnological research on rice is done by public institutes.

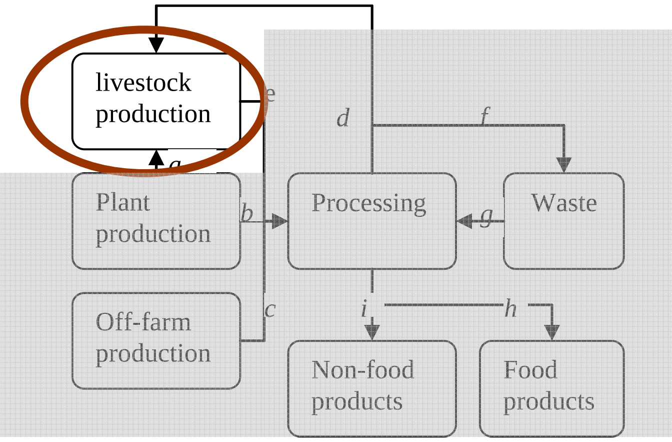
Transgenic alteration of crops is involved in many novel techniques described in this chapter. Even though each year more biotechnological altered crops are seeded, many farmers and consumers still show resistance to transgenic crops. The rate of adoption of transgenic crops, especially rice, by farmers will be one of the main factors influencing food security in the future.

3.2 Increase in livestock biomass production efficiency

World meat demand is expected to grow significantly in the coming years. If livestock production does not become more efficient, a growing amount of crop production will be needed as fodder. In this chapter, we will discuss whether an increase in livestock production efficiency is to be expected. Food conversion efficiency (ECI) is a measure of the efficiency of food conversion in farmed animals. An increase in ECI existing livestock can have a huge positive impact on global food production as livestock consumes a significant share of global plant production.

We discuss two ways of raising the ECI for the world's livestock system. Firstly, we elaborate on the possibilities and benefits of shifting from mammal/bird proteins to fish and insect proteins. Secondly, we examine whether we can expect any gain in ECI of traditional livestock (cows, pigs, chicken) in the coming years.

Figure 10: Flowchart of processes involved in farm biomass production (livestock production)



Shift from mammal/bird proteins to fish and insect proteins

Nakagaki and DeFoliart (1991) compared the ECI of the cricket *Acheta domesticus* (L.) with the ECI of conventional livestock chicks, pigs, sheep and cattle. All animals were fed the same high-quality diet. The results can be found in Table 2. It was found that the wet weight ECI of the insects was more than twice that of chicks, three times higher than in pigs, five times higher than in sheep, and almost six times higher than in cattle. Although insects have relatively high water content, the dry weight ECI of the crickets was still remarkably higher than that of the other animals. Also, when losses due to dressing percentage and carcass refuge are taken into account, the adjusted dry weight ECI of crickets is still more than twice as high as that of chicks and pigs, more than four times higher than in sheep and nearly six times higher than in cattle (Nakagaki and DeFoliart, 1991). So it seems that insects are much more effective in food conversion than conventional livestock. The fact that insects have a relatively high fecundity even increases the advantage in favour of the insects. When this higher fecundity is taken into account, the true ECI of crickets is approximately 20 times higher than the ECI of beef (DeFoliart, 1997).

Venugopal et al. (2004) measured the ECI of the fish species *Labeo rohita* (rohu). The ECIs of fast-growing transgenic rohu were compared with the ECIs of a control group of non-transgenic rohu. The results are shown in Table 2. It was found that transgenic rohu had a significantly higher ECI than non-transgenic rohu. Compared to the control group, 8-month old transgenic rohu were twice as efficient in converting the consumed food. However, commercial use of transgenic organisms raises public concerns about ecological risks, food safety and bioethics.

In Table 2 you can also find the ECI values of three other fish species, namely Nile tilapia (El-Saidy and Gaber, 2005), Turbot (Lee et al., 2003) and Atlantic cod (Rosenburg et al., 2004). From these values you can see that the ECI values vary a lot between fish species, and that in some cases (Nile tilapia and Atlantic cod) the ECI is very low compared to that of the insect and the vertebrate livestock species. On the other hand, the ECI of transgenic rohu and turbot is quite high compared to the values of the other animals. However, the values of the fish cannot be compared with each other or with the values of the insect and other vertebrate species. This is because all the fish species were fed different diets. To really say something menaingful about the ECI of fish compared to other species research must be done whereby all species are fed the same diet. Furthermore, information about dry weight ECI, dressing and carcass refuge is also needed.

In Table 4, the body composition of six different animals at market weight is shown. From these tables it becomes clear that, when you look at the percentage of proteins, insects are comparable with the other species. This finding, combined with the high ECI of the insect species, indicates that if you want to produce as much protein as possible with a certain amount of food, the best thing to do is to mass-rear the cricket.

From the experiment by Nakagaki and DeFoliart (1991), it appears that insects are more efficient food converters than conventional vertebrate livestock. What other reasons might there be to start eating insects? The nutritional value (amount of proteins, fat, vitamins and calories) of insects compares very well with that of meat and fish. Insects are rich in protein, vitamins and minerals, and a good source of iron and B-vitamins (van Huis, 2003). The quality of crude protein in insects is lower than that of protein from vertebrate animals and other high-quality protein sources. This is due to the low digestibility of insect crude protein. It seems that this is caused by the fact that some of the nitrogenous components are in the form of chitin in the integument, and humans do not produce chitinase. However, the chitin can be removed before consumption, thereby increasing the protein quality. Furthermore, several insects have been shown to be a better source of protein than most plant sources (Nagasaki and DeFoliart, 1991).

Table 3: Feed conversion efficiency of an insect species, several vertebrate livestock species and four fish species

Factors	**Cricket nymph**	**Broiler chick**	**Pig**	**Lamb**	**Steer**	**Rohu**	**Transgenic rohu**	**Nile Tilapia**	**Turbot**	**Atlantic cod**
A. Whole body live weight ECI (%)	92	48	29.5	18	14.5	72.6-93.65	121-159	1.5-3.7	?	0.74-0.88
B. A minus reciprocal of dressing percentage	92	33.6	19.5	9.7	8.6	?	?	?	?	?
C. B minus carcass trim (=adjusted wet weight ECI)	73.6	22.8	15.4	?	7.3	?	?	?	?	?
D. Whole body dry weight ECI (%)	26.4	17.3	14.4	8.4	6.8	?	?	?	46.1-107.7	?
E. C minus water (=adjusted dry weight ECI)	21.1	9.9	8.5	4.8	3.6	?	?	?	?	?

(A question mark means there is no data available. The values of the cricket nymph, broiler chick, pig, lamb and steer are found when fed with the same diet)

In many third world countries, insects are an accepted alternative for fish or meat. For example in Venezuelan Amazonia, indigenous people eat several types of insects like termites, grubs and caterpillars. Consumption of 100 g of any of these invertebrates contributed 1.2–9.4 percent of the daily fat requirement and 26–144 percent of the protein daily requirement for an adult male (Marconi et al., 2002).

Table 4: Body composition of six different animals at market weight (adapted from Nakagaki and DeFoliart (1991) and El-Saidy and Gaber (2005))

	% water	% protein	% fat
Cricket nymph	68.4-74.2	15.0	10.3
Broiler chick	64.0	18.8-28.6	4.9-14.2
Pig	50.0-52.6	12.7-14.7	29.5-38.0
Sheep	53.2	15.0-15.2	25.2-29.0
Steer	52.0-53.5	17.0-18.2	21.1-26.9
Nile tilapia	+/- 72	+/- 15	+/- 5.8

Protein is often the most expensive dietary component (Coyle et al., 2004). This, together with hazards to the environment because of fish and meat production (caused by uneaten food and/or end products of N and P metabolism which are released into the environment as soluble wastes (Cowey, 1995)), might result in the production of insect proteins becoming important for western countries too. Of course this can only happen if the western attitude towards eating insects changes. It seems quite unlikely that European consumers will start eating recognisable insects. A possible solution for this problem is to add insect products or insect proteins to, for example, meat (hamburgers, minced meat) or microwave meals. However, studies from the Profetas network point out that consumers like real meat from normal animals even when they are eating 'out of the microwave'.

Increasing the feed ratio of traditional livestock

An increase in the feed ratio of existing livestock can have a huge positive impact on global food production as livestock consumes a significant share of global plant production. Experts expect that the rise in productivity of new races will continue for at least another 20 years. This means that cows will continue to produce more milk, and pigs will fatten more quickly. Every year the amount of weight a pig can gain in one day increases by 10 grams. Nowadays, the process from egg to slaughterable chicken takes 40 days. Each year this process becomes a day shorter.

As miraculous as this may sound, the increase in productivity per unit of time is not accompanied by a comparable rise in feed efficiency. Feed efficiency is hardly increasing at all. The rise in fodder efficiency of livestock in the past was based on a change in meat composition. By reducing the share of fat in meat, less energy is needed to produce a certain amount of meat. The fat content of modern races cannot be lowered any further.

In China, traditional pigs are two to three times less efficient as their modern high-yielding colleagues. Fifty percent of all pigs worldwide live in China. Most Chinese pigs belong to traditional races that produce fatty meat. It is to be expected that China's meat consumption will increase dramatically in the coming decades. The amount of fodder needed to produce this meat depends heavily on the type of pigs Chinese farmers are will keep in the future.

Conclusion

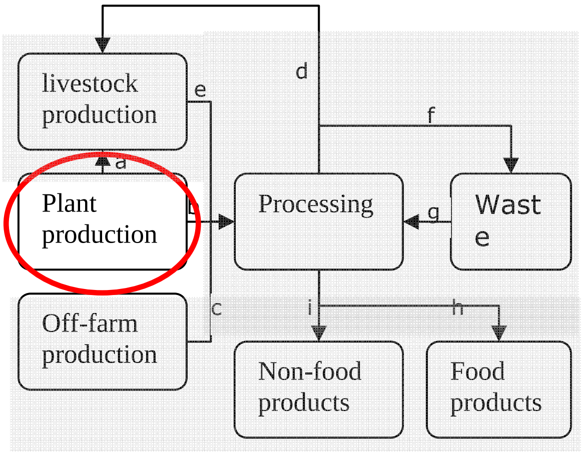
Shifting from traditional livestock species to cold-blooded animals is the only way that modern livestock systems can be made significantly more efficient in terms of ECI. Theoretically, the use of insects rather than traditional livestock can increase farm biomass efficiency by 400 to 600 %. However, consumer acceptance of insect meat is likely to be low.

3.3 More efficient processing of food and fodder

Almost all food is processed before it gets to the table. In the western world the majority of the processing is done in big plants. During processing, the amount of food available for human or animal consumption can be increased in two ways. A) By increasing the processing efficiency, so that less waste is produced (*f* in flowchart) and more food (*h* in flowchart) or by re-processing the waste so it can be used as food or fodder again (increasing *g*-flow in chart).

Planet earth's more than three billion head of cattle, sheep and goats is expanding daily. In order to be able to feed these animals in the world of tomorrow, either more fodder sources are needed or the existing sources have to be used more efficiently. A recently developed processing technique, called bio-refinement, makes it possible to decompose leaves into amino acids, starch, and food fibres. These products can then be used to produce starch and protein products for human consumption, high-quality animal fodder, and chemicals, or to produce energy. In the last part of this section, I will explore the potential of bio-refinement for increasing the world's fodder production.

Figure 11: Flowchart of processes involved in farm biomass production (processing)



In this section, we will discuss improving the efficiency of processing. According to experts, the efficiency of food processing can be improved; for example, potatoes can be peeled more thinly. The technical means are available, but economic constraints exist, making this a socio-economic issue.

Re-use options for food waste

The European food industry alone produces 222 million tons of solid waste. This sounds like an enormous amount, however much of this waste is already destined to be re-used. Current use of food processing solid waste can be arranged in a hierarchy of added value, with the production of food (1) products being the highest-value option and disposal being a negative value option. A second high-value option is chemical production (2). This application is small, but growing, as the opportunities are being identified and developed. Where possible, the next level of use for these materials is as animal feed (3). Fuel (4) value is the next lower use. A low-value use is for composting or land application (5) with limited soil amendment value. Otherwise, these materials are discharged to the sewage system or buried in a landfill (6). (Muñoz, 1991)

An increase of food or feed from agricultural waste can only be expected if there are technologies available that are capable of effectively increasing the value of the product. In other words, waste that is used to produce fuel or compost, or which is not used at all (landfill) nowadays should be converted to animal feed or food products. A shift from production of chemicals to food can also increase the food supply.

AwareNet, the EU-financed thematic network for prevention, minimisation and reduction of waste from the European industry, studies waste flows from European food industries. A summary of the data presented by *AwareNet* is shown in Table 5. It can clearly be seen that the sugar industry is responsible for the largest share of food waste in Europe. However, the total amount of waste is not that important, as we are only interested in the parts that might be useful for producing food.

Table 5: Production of waste per food product (AwareNet, 2004)

Food product	*waste /by product ton/year*	*Percentage of total*	*Products now used for fuel, compost, or that are buried in landfills*
Beef	5,583,110	3%	< 10%, manure/straw now composted
Pig	8,465,990	4%	< 10%, manure/straw now composted
Poultry	4,903,190	2%	12%, bones and feather
Fish	6,336,607	3%	<1%
Dairy	57,103,325	26%	1%. cheese smear
Sugar	100,572,508	45%	12%, leaves, weeds, tails, soil, in total 100 kg per tons of sugar beet
Other/ vegetable	39,139,441	18%	<1%
Total	222,104,171	100%	

It seems to be safe to assume that waste that is used as a source of chemicals nowadays will not be used as a source of food or animal feed in the future. *AwareNet's* review of technologies under development does not point to any development in that direction. Furthermore, the value-added money will be low. That means that possible food gains have to be found in by-products that are currrently being used for fuel, compost, or that are buried in landfills. Several authors describe techniques for turning manure, bones and feather into feed for poultry. These techniques are controversial because of the risk of prion disease outbreaks. Therefore, I consider these sources unsuitable for food or fodder production. The 12% waste that is not yet being used from sugar production is almost only soil, making it worthless for re-use purposes other than returning it to the sugar fields. (Wanapat, 1990)

Bio-refinement

A recently developed technique, called bio-refinement, makes it possible to decompose leaves and other organic material into amino acids, starch, and food fibres. Bio-refinement can increase the quality and the efficiency of the fodder crops used nowadays. For example: Dutch grass is very high in nitrogen content. Cows do not use most of the nitrogen, so a large part of it is wasted. If the Netherlands would refine the grass that is now turned into hay, the protein content of fodder for cows can be lowered. The amount of proteins that can be extracted from grass in the Netherlands would be enough to replace the entire import of soy protein. In the Netherlands, the cost of grass protein is equal to the cost of soy protein (Sanders, 2004). In countries that lack huge harbours, like Germany, the price of grass protein will be lower than the price of soy protein. We should note that it is only economically feasible to extract protein from grass if its nitrogen content is high enough. In most pastoral areas, like the pampas of Argentina, nitrogen levels are too low.

Fortunately, there are many other crops with higher nitrogen contents than grass. Ghana, for example, could be self-sufficient in protein production if it were to cultivate a legume crop like alfalfa[4] on two percent of

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[4] Alfalfa was given as an example by Johan Sanders, but is not a suitable crop for Ghana because of its climate.

its land area. Like Dutch grass, alfalfa is too rich in nitrogen to be used as fodder directly. Pigs cannot digest alfalfa at all. After refinement, more balanced fodder can be produced for any form of livestock.

Bio-refinement of waste products from the food industry and from leftovers of crops that are normally left in the fields can increase the production of fodder as well. For example, leaves from the cassava (*Manihot esculanta*) are nowadays hardly used because of their high cyanhydric acid content. If all cassava leaves were to be harvested and turned into crude protein through bio-refinement, the protein production would equal one-fifth of the world's soy protein production. When fertilized, the protein production of a hectare of cassava can even exceed the production of one hectare of soybeans (Wanapat, 1990). Like the grass case, bio-refinery of cassava will not be suitable for all cassava growing areas. The technique is capable of handling almost all types of leaves with some N content. Bio-refining of the crop residues of soybeans might increase protein production from soy by 5%. Leaves of other leguminous crops like peanuts are also very suitable.

Table 6: Protein potential of cassava after bio-refinement

	low N gift	*high N gift*	
World cassava area	17.570.044	17.570.044	ha
Cassava hay production	3,4	3,4	ton/ha
Protein content	20%	30%	
Crude protein yield	0,68	1,02	ton/ha
Potential cassava protein production	1E+07	2E+07	ton
Expressed in percentage of soybeans	18%	27%	
World soy protein production	7,E+07	7,E+07	ton

Conclusion and discussion

Extrapolating Europe's situation to the rest of the world, we can conclude that we cannot expect a large rise of food from the waste of agro-industries. The African situation however might very well differ from the European one. FAO and Cargill reported that large amounts of usable by-products are left unused. (Inter Academy Council, 2004) Unfortunately, recent data from Africa are not available. Another recent development that might make it possible to make better use of agro-industrial by-products is bio-refinement. Bio-refinement can use those parts that are already being used for fodder production, but increases the efficiency of their use. There is not enough information available about the current use, quantity and quality of the existing waste fodders to estimate the potential of bio-refinement. The suitability of bio-refinement for the production of animal fodder from non-waste materials depends on local conditions. The price of the protein produced has to be lower than the price of other available protein sources. In areas where soybeans are grown, like Brazil and the United States, bio-refinement will probably not be cost efficient. However, as bio-refinement might also be used to produce chemicals, fodder might be produced as a 'by-product'.

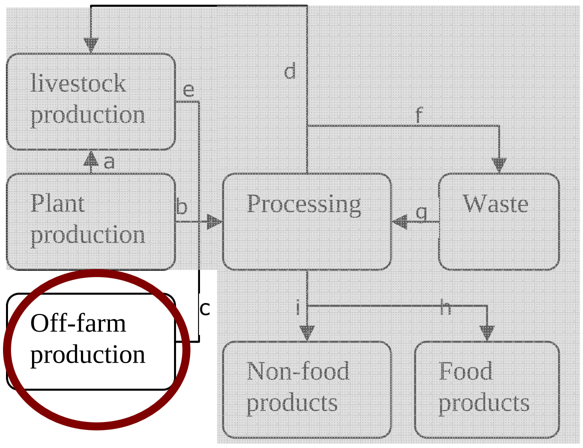
In the past few decades, Europe has become increasingly dependent on cheap protein imports. This technique can provide Europe with a new source of cheap proteins. If it is almost economically feasible for grass in the Netherlands, it will be feasible in other European countries because protein prices are lower in the Netherlands. The European Union now consumes 25 % of the world production of soybeans. Soybeans are not only used for protein production, but also for oil. That means that an increase in European protein production might not influence the European soybean imports. However, it will increase the global supply of proteins.

In addition, the success of bio-refinement for fodder production depends on the way that animal production systems are organized. It might be that giving a fodder mixture that is reduced in nitrogen by bio-refinery is more efficient than feeding cows with grass alone, but the same effect might be reached by mixing with low protein-ingredients like beet pulp. Although there are still many uncertainties, it is very well possible that this technique will increase world protein production by more than ten percent.

3.4 Non-farm biomass production

In this section, different kinds of non-farm biomass production systems will be introduced and discussed. These are systems that supply raw products for further food production similar to plant- and livestock production. This is done because of the fact that the production of non-farm biomass may in future be of significant importance for the world availability of food. Different types of non-farm biomass production systems will be discussed. Each production system will be described, its importance will be explained and the possible bottleneck for large-scale implementation will be outlined. The emphasis in this chapter lies on the production of protein.

Figure 12: Flowchart of processes involved in farm biomass production (non-farm)

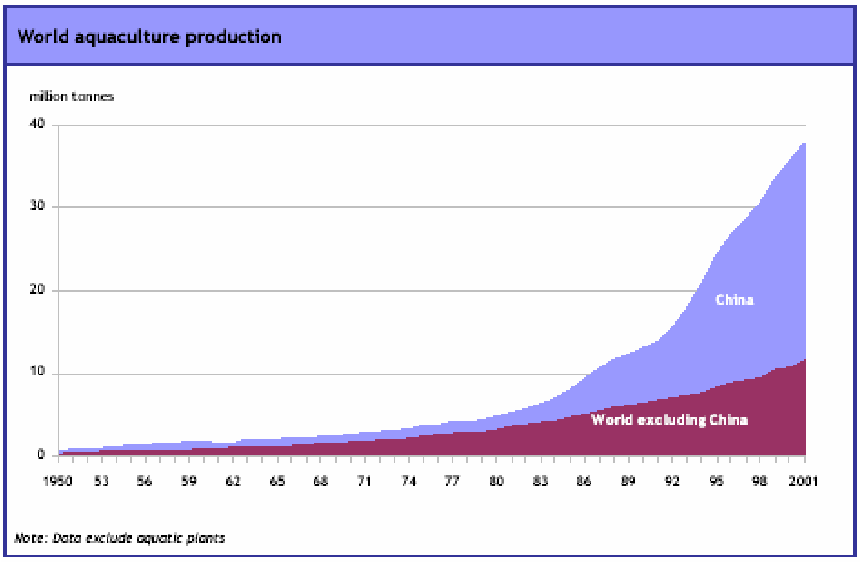


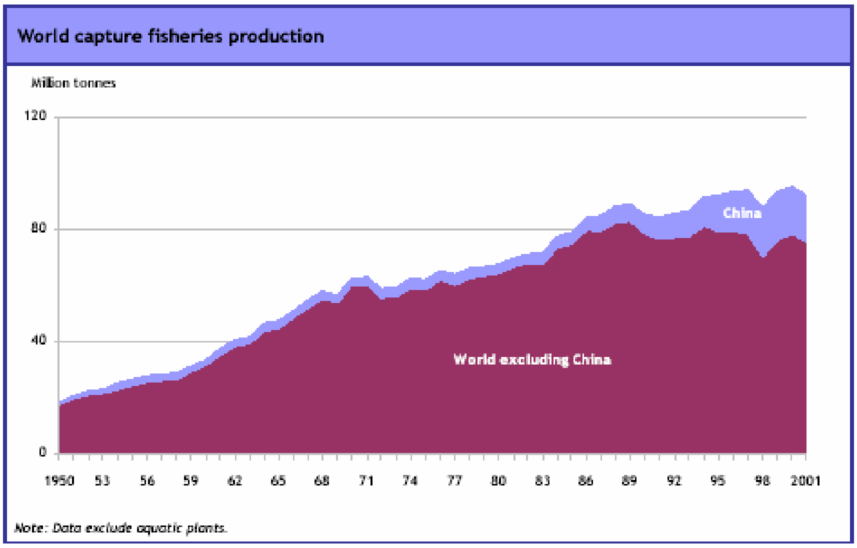
Proteins are essential for all processes in the human body. In this respect, it is essential to think differently. However, we need to find new ways of producing these (Brandenburg, personal communication). Proteins can be produced by animal and plant production systems. However, plants do not produce the essential amino acids in large quantities, wheras animals do, as algae for instance (Brandenburg, personal communication). In this chapter, old and new marine production systems are discussed first, after which the production of protein through algae (including a case study of *Spirulina*) is described in more detail.

Traditional fish production systems

The expert group discussed two matters concerning fish and fish production. The first was the production of animal protein through fish. About 10-15% of all animal protein comes directly from the sea (Brandenburg, personal communication). It would be very strange to say something about the availability of food while ignoring such an important food source. The second was the potential of producing more animal protein with less vegetable protein through the production of fish, since the conversion ratio of feed to meat is higher with fish than with for instance cows. Both issues were addressed during the meeting. This report defines the amount of fish from the sea and other water bodies harvested at this moment and I will go into the trends that have been observed in the last few decades and extrapolate them to future prospects.

Figure 13: World aquaculture production and world capture fishery production (FAO, 2002)




World capture fisheries production

Note: Data exclude aquatic plants.

In fish production, several systems are important: wild capture, controlled production, and everything in between. Wild capture is defined as a system in which fish are captured that have not directly been fed by humans. In aquaculture (also called controlled production) small fish are placed in a water body, fed, possibly protected against diseases, and harvested when the time is right.

The world production of both systems in 2000 reached a new high of 130.25 million tonnes, an increase of 11.9% since 1995, including the production in China. If we were to exclude China, world production remained flat, the 2000 figure of 88.68 million tonnes being only 0.8 percent higher than the 87.95 million tonnes achieved in 1995 (Appendix 1). The total production in 2000 was still increasing (FAO, 2002).

Limited wild fish stocks in both oceans and inland waters place significant constraints on the total wild capture production. Total capture production, at 94.65 million tonnes in 2000, was only 3.0 percent higher than the 1995 level of 91.87 million tonnes; excluding China, the production decreased by 2.1 percent. The wild capture of fish seems to have reached its maximum. It is feasible that the production has to decrease significantly before a sustainable system can be established (FAO 2002).

The total growth of fish production was mainly caused by the sharp increase in aquaculture production (again mainly in China). Because fish in aquaculture have to be fed with other sources of food (fish from natural catch and/or agricultural products, it can not be considered as a non-farm production system. This will be taken into account when discussing the shift to other farm production systems and feed ratios.

The projections of world fishery production in 2010 range between 107 and 144 million tonnes, of which about 30 million tonnes will probably be reduced to fish meal and oil for non-food use. Estimates of quantities that will be available for human consumption range between 74 million tonnes and 114 million tonnes. Table 6 illustrates this. Much of the increase in fish production is expected to come from aquaculture, which is growing rapidly. The contribution from capture fisheries will depend on some further development and on the effectiveness of fisheries management. Improved management of currently over-fished stocks could provide an increase of between 5 and 10 million tonnes, whereas continued over-fishing will lead to declining production (FAO, 1999).

Table 7: Lower and upper projection levels for 2010 (million tonnes) (FAO, 1999)

	Present situation[2]	*Pessimistic scenario*	*Optimistic scenario*
Capture fisheries	95 [2]	80	105
Aquaculture production	35 [2]	27	39
Total production	130 [2]	107	144
Less fish for non-food uses	?	33	30
Available for human consumption	?	74	114

Whenever a natural population is exploited, there is a risk of over-exploitation: too many individuals are removed and the population is driven into biological jeopardy or economic insignificance – perhaps even extinction (Townsend et al., 2003).

New marine production systems

In addition to the production of fish in more traditional systems, some new systems for marine production will be discussed. As concluded in the previous section, the limit to wild capture fish production has almost been reached. However, the demand for fish protein is likely to increase. Furthermore, the competing claims on land

and fresh water are increasing[5], although this seems less the case with the marine production area. Therefore, the potential for new marine production methods seems enormous. Luiten defines three different types of new marine production systems based on the location (Luiten, 2004): (i) new marine production systems in the ocean, (ii) on tidal plains (half sea, half land) and (iii) by bringing sea onto the land. In this subsection, different examples of new marine production in the ocean will be discussed whilst the method of bringing the water onto the land will be discussed in the next subsection. The second option of tidal plains will not be discussed, since this system is largely a combination of the former two.

New marine production in the ocean
The book 'Zee in zicht' presents different experiments for developing new marine production systems. Two interesting experiments that will be discussed in this section are (i) the tillage of the ocean and (ii) the construction of sea-wings.

Tillage of the ocean floor could be done to obtain a higher yield per area of ocean. By tilling the ocean bed and creating a perfect habitat for desired species, production can be increased. Fishermen would become farmers ploughing and harvesting the oceanic land as they please. According to the author, this would result in higher fish production and catches. However, more research has to be conducted to collect more evidence on efficiency and the possible detrimental effects of this method.

The other new marine production system for the open sea is the so-called sea-wing. This is a fully autonomous aquaculture basin in the ocean, supplying energy through the motion of the waves and through wind energy. This energy can then be used to form H_2-feeding hydrogen bacteria in the basin, which is feed for the fish in the basin. This can all be done without requiring any external energy or claims on other resources. However, even though this sounds an excellent method, no working prototype has been built to date.

It can be concluded that new marine ocean production systems are in a very experimental phase. Only very limited information is available on the possible production capacity and therefore on the impact of these systems on global food supply. For now there is no proof that these new marine production systems will significantly contribute to the global availability of food.

Bringing the water to the land: the example of algae production
In this subsection, the importance of protein production and the possibility of protein production with algae will be discussed. In this report I wish to define how much algae are being produced at this moment, and why. Furthermore, I wish to highlight the trend observed in the last few decades, the prospects for the future, and what conditions might be necessary to achieve these goals. I will introduce *spirulina* as a special case for algae production.

In the general introduction, the importance of protein for the human body was discussed. Besides proteins, there are also other products, like fish oils, that are of importance for the functioning of the human body. Fish oil contains Omega-3 fat acids and is rich in anti-oxidants like flavonide, carotene and folic acid. At the moment, fish oil is consumed through the consumption of fish. As has become clear from the previous paragraph, the wild catch of fish is limited in the old marine production systems and so other sources of fish oil will have to be found. Algae might be able to cater for this need.

The cyan bacteria and micro algae such as *Chlorella*, *Spirulina* and *Dunaliella* possess a great potential; not only for the production of traditional food algae, but also for the extraction of valuable chemicals such as beta-carotene (Oliveira, 1999). "Both *Spirulina* (and *Chlorella*) are microscopic plants that grow in fresh water. They are actually called micro-algae, since they are microscopic forms of algae. […] These micro-algae contain a great array of nutritional elements: vitamins, macro minerals, trace minerals, essential fatty acids, protein, nucleic acids (RNA and DNA), chlorophyll, and a vast spectrum of phyto chemicals". (Adams, 2004) They have a green appearance due to their chlorophyll content. Spirulina grows in water bodies under influence of the sun.

Currently Spirulina is produced in large open water tanks to which nitrogen, phosphate and carbon dioxide are added. The tanks are exposed to the light and the water in the tanks is propelled to move the water - and thus the cells - around and expose them to the light. "The optimum temperature for *Spirulina* growth lies in the range of 30 to 35 °C"(Oliveira, 1999).

Productivity of *Spirulina* algae can reach up to 200 tonnes/ha when produced under the ideal circumstances. But as the dry weight is only between 10-12 %, the maximum production of dry weight per ha is between 20 and 24 tonnes. The high productivity of Spirulina is also partly caused by the fact that almost the entire organism is of use. Spirulina has a harvest index of almost one hundred percent, as Spirulina is a single cell and water-borne organism: it has no roots, stems or other 'unproductive' parts (Brandenburg, personal communication).

More than thirty years ago, the first commercial business started producing algae, *Spirulina* (currently considered to be one of the most interesting commercial algae). At this moment, more than 30 years after the initial commercial production, the use of algae for food production is still quite low – the worldwide production of *Spirulina* is no more than 3000 tonnes of dry weight a year.

The current market price of one kilogram of *Spirulina*[6] produced in Thailand is about six euros. Six euros for a protein source is still relatively high considering that soybean costs about half a euro per kilogram (Quist et al., 1996). However, comparing proteins from soybean with proteins from *Spirulina* is rather unfair as the quality of their components is so different. Spirulina, for example, is rich in Omega-3 fat acids, carotene and B-vitamins. These components are not present in proteins produced by soybeans. Thus, even though the production costs of algae are higher, there are still opportunities for algae. Wijffels (personal communication) concluded that the chances of algae becoming protein producers for animal feed are quiet small. Algae will not be used unless there is a demand for the special components supplied by algae.

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[5] Chapter on competing claims on natural resources

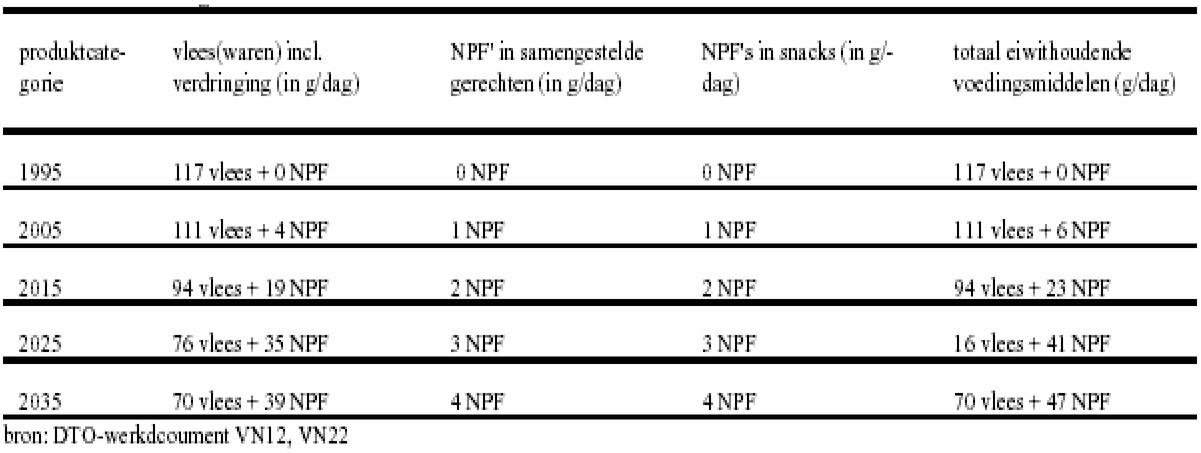
[6] Spirulina is taken as an example as it isthe cheapest algae on the market at the moment.

Apart from the use of the special components in animal feed, algae have a good chance of becoming (larger) suppliers of proteins and vitamins of (health) foods. This is very likely when you consider the stagnating or possible decreasing natural catch of fish and the new knowledge on the necessity of consuming Omega-3 fat acids. An alternative source will have to be found and one of these sources might very well be algae. Though the price gap between soybean protein and algae protein will probably decrease, soybean protein will always remain cheaper than algae protein (Wijffels, personal communication).

Problems regarding the production of algae are the following:

- Finding an effective production process for algae production is quite complicated, as the system tends to be very dynamic. The population changes constantly as does the concentration of grams of algae per litre of water. This means that the speed of water circulation has to be variable and the harvesting time has to be chosen carefully.
- Harvesting of algae is, in most cases, a complicated process due to thecentrifugal equipment that needs to be used.
- One of the problems with the production of algae is the upscaling of the production process since in agriculture upscaling this is never a linear process. In the production of algae, this is even more difficult as they are three-dimensional, in other words, all different cells float in the water basin, which is a three-dimensional area. All the algae have to be close to the surface for the same amount of time if homogeneous growth is to be achieved.
- Another problem is the gamma factor. People want to eat steak and potatoes. Algae, just like soybeans, just do not taste good so they will need to be manufactured into something more attractive for consumption.

Table 8: Consumption of protein-containing foods per capita of the Dutch population now and prognoses of the future (Quist et al., 1996)



produktcategorie	vlees(waren) incl. verdringing (in g/dag)	NPF' in samengestelde gerechten (in g/dag)	NPF's in snacks (in g/-dag)	totaal eiwithoudende voedingsmiddelen (g/dag)
1995	117 vlees + 0 NPF	0 NPF	0 NPF	117 vlees + 0 NPF
2005	111 vlees + 4 NPF	1 NPF	1 NPF	111 vlees + 6 NPF
2015	94 vlees + 19 NPF	2 NPF	2 NPF	94 vlees + 23 NPF
2025	76 vlees + 35 NPF	3 NPF	3 NPF	16 vlees + 41 NPF
2035	70 vlees + 39 NPF	4 NPF	4 NPF	70 vlees + 47 NPF

bron: DTO-werkdcoument VN12, VN22

The two main problems that have to be overcome are the following: price and improvement of the production technology. This latter refers to the improvement of bioreactors, stem sources and biotechnology (Wijffels, personal communication). The DTO[7] on the other hand forecasts a large share in the consumption of novel protein foods (NPF[8]) that are used in combination with meat in meaty products for the year 2035 (Quist et al., 1996). Table contains a list of the prognoses.

As stated already, the limit to wild capture fish production has almost been reached. If no sustainable management can be found and applied, the production will decrease further. For this project, it would be useful to take into account the current production of wild capture fisheries, or at least the range between the 80 and 105 million tonnes of fish captured in the wild, this all in accordance with the projection of World Fishery Production in 2010 by the FAO. However, the increase in fish production is expected to originate from aquaculture as this sector is still growing rapidly.

In this project, we are looking to forecast whether the quantity of food available will be sufficient in the coming decades. In this respect it is necessary and desirable to predict the importance of new marine production systems. While more people are becoming aware of the health aspects of consuming fish, the availability of fish is decreasing. The high production (potential) of algae may result in algae production on a much larger scale than is being considered at the moment. Competing claims on land and water, and the reduction of pollution may also provide positive impulses to produce more algae. However, algae protein will probably never become cheaper than soybean protein. It is not very likely, therefore, that algae will come to replace soybean protein production.

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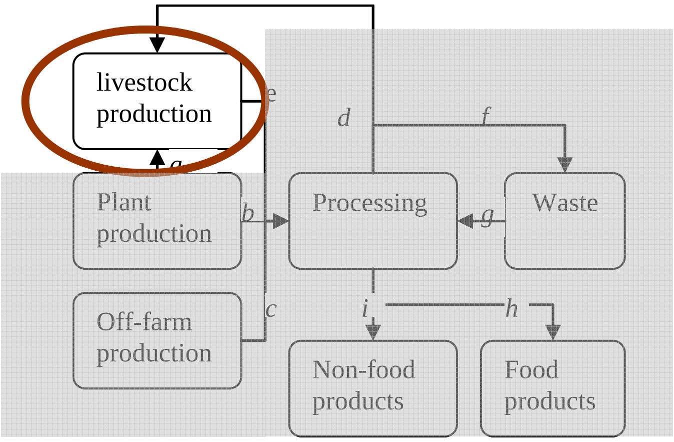
[7] DTO is an interministerial research group in which five Dutch ministries work together to achieve sustainable technology development in the Netherlands (and the world) in the coming decades.

[8] In this study, the algae Spirulina is considered to be the most promising NPF.

3.5 Substitution of vegetable products for meat

The global demand for meat is increasing. Currently, 735 million tonnes of cereals are used as animal feed (FAO, 2004). Substitution of meat by vegetable products that are nutritionally comparable might therefore strongly decrease the demand for fodder and space. In this paper we will go into the possibilities for meat substitutes in the future.

Figure 13: Flowchart of processes involved in farm biomass production (substitution)



In this section, we discuss the possibilities for shortcutting the uppermost arrow of meat production by vegetable-based meat substitutes.

Techniques that can be used to produce marketable products based on vegetable materials that are able to replace meat totally are under development. The preconditions that have to be fulfilled are: 1) the product has to be as nutritive as meat. In order to achieve this nutritional value, products have to contain four essential amino acid types, as well as a range of vitamins and micronutrients that are normally only available in meat products. 2) The product has to be attractive for consumers.

It is possible to fulfill the first precondition. Recently developed advanced techniques make it possible to convert vegetables into food products that are as nutritive as meat. For the production of these meat-like products, crops like soybeans or peas can be used. Most of the pulses are used nowadays as an ingredient of fodder. However, making the product appealing for consumers is a much greater obstacle. Attractiveness does not depend much on the price of the product. Taste and structure are more important. According to research done by the Profetas network, even vegetarians want their meat substitute to be really meat-like even when it is hidden in ready-to-take meals from the supermarket. (Jongen and Meerdink, 2001) Besides that, it is more or less common sense among scientists that loving meat is a genetic characteristic of humankind. Humans who have a diet rich in proteins have a higher fertility than humans who consume a diet low in proteins. In many societies, the consumption of meat is associated with being wealthy and powerful. Another important element of attractiveness is the civil status consumers acquire by consuming meat. However, the important meat substitutes in Asian society, like tofu, tempé and seitan, do exist and are relatively popular, but they are still considered to be the food of the poor.

Although eating artificial meat is becoming a bit of a trend among highly-educated western people, a big move towards vegan products, regardless of their nutritional value, taste or price, is not very likely in the near future. Therefore, it is not likely that the introduction of new, better and tastier meat-like plant-based products will affect the potential food supply.