Utilising intrinsic robustness in agricultural production systems

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Abstract: This paper explores the potential of utilising robust crops and livestock for improving sustainability of agriculture. Two approaches for dealing with unwanted fluctuations that may influence agricultural production, such as diseases and pests, are discussed. The prevailing approach, which we call the 'Control Model', is to protect crops and livestock from disturbances as much as possible, to regain balance with monitoring and intervention and to look for add-on solutions only. There are a number of problems associated with the Control Model, including reduced animal welfare, environmental pollution and low public support. An alternative approach, which we call the 'Adaptation Model', is based on reducing the consequences of disturbances rather than taking disturbances out. Robust Design may be a promising methodology to utilise robust components and design the production process for minimal variation. For crops and livestock this means utilising and supporting their intrinsic ability to deal with disturbances by adaptation. Four main areas of research required for adopting the Adaptation Model were identified. Firstly, it is necessary to raise the awareness of the two approaches with all parties involved to stimulate innovation. Secondly, the methodology for robust design within and across animal and crop production systems needs further development. Thirdly, there are still many unanswered questions regarding optimal utilisation of biological robustness mechanisms, which requires technical research. Fourthly, as diversity of production systems increases, dissemination of knowledge will have to change from dissemination of solutions to dissemination of methods to identify the best solution for a specific context.

"We cannot solve the problems we have created with the same thinking that created them!" [Albert Einstein]

Introduction

Following the Food and Mouth Disease outbreak in 2001, a group chaired by Dr Wijffels was invited by the Minister of Agriculture to advise on the perspectives for sustainable animal production in the Netherlands. Their report (Ministry of Agriculture and Food Safety, 2001a) and the 4th National Environmental Policy Plan (Ministry of Housing, Spatial Planning and the Environment, 2001) were the start of a change in governmental policy in favour of a transition to a sustainable agriculture (Ministry of Agriculture and Food Safety, 2001b, 2002).
This transition requires a different kind of knowledge and expertise, and new ways of collaboration between commercial and research organisations. Supporting this process is the aim of TransForum. For this purpose, they invited scientists to explore existing expertise and expertise to be developed for key focus areas. The assignment for this paper was to explore the potential contribution of intrinsic robustness mechanisms for achieving a more sustainable crop and livestock production.
TransForum define a sustainable agricultural sector as follows when compared with the current situation[3]:

- It is economically sound;
- It provides high-value products and services;
- It is considerably less demanding and less detrimental to the environment;
- The minimum level of animal health and welfare is higher;
- It results in an attractive countryside;
- It is supported by the general public and well integrated within society.

We tend to evaluate the functioning of agricultural production systems as the average performance on the above-mentioned criteria under conditions that are considered to be "normal". However, as conditions vary and disturbances take place from time to time, stability of the production system is also an essential feature of its performance. Sensitive systems may on average meet the sustainability criteria, but may show strong deviations in case of unfavourable conditions. A sensitive farm may be profitable on average, but go out of business due to liquidity problems when prices are low.
There are two approaches to keep a system in balance and these are not mutually exclusive. The one approach is keeping away disturbances and the other approach is minimizing the impact of disturbances.

3 http://www.transforum.nl/transitie_duurzame_landbouw.htm#innovatie

The two approaches can be visualised by keeping a ball in position. On a flat surface, the ball only remains in position if it is protected from disturbances as draught. If the protection is unsuccessful, the ball has to be pushed back in position. In the second approach, the energy is spent on the design of the surface. If the ball is moved because of a disturbance, it rolls back in position afterwards (see Fig. 1). In both cases, the ball is in balance in ideal conditions, but the balance is more stable in the latter case.

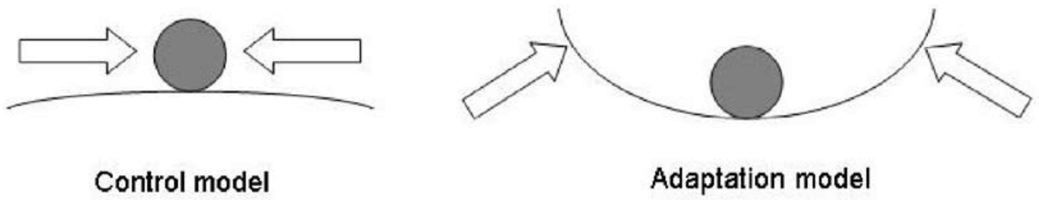

Figure 1. Under the Control Model, keeping the ball in position is by design dependent on protection and interventions, but under the Adaptation Model, returning to the original position after a disturbance is part of the design.

In this paper we contemplate approaches to achieving stability in agriculture. We argue that the current approach is mainly based on keeping away sources of variation and highly dependent on continuous monitoring and intervening. We call this approach the Control Model. We also set out the contours of an alternative model based on allowing and supporting systems to cope with disturbances through adaptation. In this case, maintaining stability in the face of foreseen and unforeseen problems is an integral part of the design process. We call this the Adaptation Model. It must be stressed that the Adaptation Model is not synonymous with organic farming, although many aspects of the Adaptation Model are implemented in organic farming. For example, the use of artificial fertilizer or genetically modified organisms is prohibited in organic agriculture, whilst under the Adaptation Model, there is no a priori restriction of methods.
It is evident that the Adaptation Model is closely linked with concepts as robustness (in the narrow sense: ability to switch between underlying processes to maintain the balance), resilience (ability to regain the balance after a disturbance) and resistance (insensitivity to disturbance) [4]. Yet none of the three concepts describes the Adaptation Model fully on its own. In the remainder of the paper we will use 'robust' and 'robustness' in the broad sense, which is minimal variation in a target feature following a disturbance, regardless of whether it is due to switching between underlying processes, insensitivity or quickly regaining the balance.
The objective of this paper is to discuss the potential for utilising intrinsic robustness mechanisms for achieving an inherently stable and sustainable agriculture.

4 For a system-theoretical discussion of robustness and related terms, see http://discuss.santafe.edu/robustness or Jen (2005).

The Control Model

Prior to World War II, agriculture in the Netherlands was characterized by small-scale production with substantial variation in production systems within and between regions. Plant and animal breeding was mostly local or regional and many local varieties existed for the various species. The post-war Dutch and European agricultural policy, aiming at securing a minimum level of food production, stimulated large-scale farming at the expense of small farms. In 1958, this common practice became official policy. In the process, agriculture became technology-driven with a single objective: maximum production at minimum cost.
These changes translated to designs for maximum productivity per unit, high labour efficiency and low production cost. Production was stabilised at the maximum level by keeping any disturbances away from animals and crops as much as possible, for example through killing bacteria with antibiotics and heavy pesticide use. Scale-enlargement caused the shielding from threats to shift from individuals to ever-increasing groups and acreages. This has lead to beef, veal, pig and poultry production systems with high concentrations of animals per farm, low labour requirements, a high level of automation and protective environments. Crop production systems were characterized by the large-scale cultivation of monocrops with high fertilizer and pesticide input.
These systems show many features of the Control Model. The paradigm underlying the Control Model is that crops and livestock can be completely controlled and manipulated to attain maximum production and eradicate threats and disturbances. This protection involves frequent and intensive human interventions and neglected inherent robustness of the production system.
Although this approach was very successful in improving productivity, a number of problems became apparent. These problems concern the efficacy and the negative side-effects of the Control Model. Firstly, imperfect implementation of the intended design as well as freak incidents may have dramatic consequences, especially when the number and the concentration of animals or plants are high. This includes outbreaks of infectious diseases and in animal production, overburdening or a chronic stress response, if animals fruitlessly try to adapt to the adverse conditions. Secondly, the protection may only be effective temporarily, because of pests and pathogens developing resistance. Thirdly, negative side-effects include inadvertent environmental pollution, loss of biodiversity, loss of diversity of production systems and lack of public support.

The key features of the Control Model at the levels of individual animal or plant, crop, herd and production chain are:

1. Protection from exposure to disturbances as much as possible;
2. Maintaining the balance is by design dependent on monitoring and intervention. Interventions to regain the balance at one level are often applied at a higher level;
3. It is implicitly assumed that new problems or demands can be solved with add-on technology

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Animal production

Infectious animal diseases

Infectious diseases on the list of "Diseases Notifiable to the OIE (World Organization for Animal Health)" [5] are not considered in this paper, because dealing with these diseases is governed by international agreements.

Endemic infectious diseases are a serious problem for current animal production systems. Infectious diseases rarely fade away in these systems, because of the high concentration of animals and the constant influx of unchallenged animals. An outbreak of an infectious disease therefore often has long-term consequences for the profitability, because of higher mortality, higher veterinary costs and lower productivity. Avoiding outbreaks of disease has become a very critical issue in animal farming. Given their existing production system, there is little farmers can do but to increase biosecurity, and veterinarians advise accordingly. It is now common in animal production to restrict the number of visitors to the farm to the minimum, to have shower facilities or provide visitors with boots and over-alls, to restrict intake of animals and clean and disinfect pens regularly. This increases the cost of production substantially, but within the given system it is cost-effective.

For an animal, an infectious disease may pose a threat to its life and welfare. Developing the immune system and mounting an immune response therefore get priority over production traits. For this reason, farmers and veterinarians tend to combat the pathogen rather than utilise the animal's immune response. Apart from vaccinations and stimulating colostrum intake, there is hardly any structured approach to training the innate and adaptive immune system. This has lead to scientists extrapolating the hygiene hypothesis from humans to farm animals (Van der Weijden and Schrijver, 2004; Van Eden, 2005). They hypothesize that the immune system of farm animals is insufficiently challenged because of hygienic conditions, which would leave the animals vulnerable to otherwise harmless micro-organisms. In other words, the reliance on human interventions leaves inherent mechanisms to deal with pathogens unused and underdeveloped. This view, however, is highly controversial among veterinary scientists.

More recently, pressure from the production chain has pushed farmers even more in the direction of freedom from certain micro-organisms. Farmers have the obligation to prove that their stock is free of certain micro-organisms, for example Salmonella spp. in the case of broiler producers. If they fail to do so, they risk a penalty or may even lose their contract.

Overburdening of animals

The experience of the last four or five decades has provided a wealth of information regarding maximisation of production from farm animals through breeding, feeding, housing and management. The average milk production per cow has increased from just over 4,000 kg to nearly 9,000 kg per 305 days lactation. Pigs reaching 100 kg of body weight in 130-140 days are no longer exceptions. Broilers weigh more at 40 days of age than many mature laying hens of 20 weeks and older.

Animals with high levels of production often struggle in suboptimal conditions. Suboptimal conditions under the Control Model imply that interventions at herd level to regain the balance at animal level, as envisaged in the design, don't take place or are ineffective. Dairy cows at the peak of lactation often stop the oestrous cycle temporarily when they are in a negative energy or protein balance. In this way the body protects the cow against complete depletion of body reserves. In other cases, the body is not able to cope with the high level of production in suboptimal conditions. Beef cattle, slaughter pigs, broilers and turkeys often accumulate body weight so rapidly, that slippery floors, overstocking and poor housing facilities cause damage to feet, bones and joints. It can equally well be argued that it is the genetic potential, the actual high level of production or the suboptimal environment, which is responsible for the overburdening. Breeders have the responsibility to genetically select for the full range of existing production systems and farmers should aim for a level of production that animals can sustain given the conditions on the farm, or otherwise improve the conditions.

Chronic stress in animals

A chronic stress response is the result of structurally not fulfilling certain needs. Imperfect implementation of the Control Model at the level of the production system will invoke an adaptive response of the animal, but since the design of the production system relies on interventions for maintaining the balance, expression of the adaptive response is not supported or even counteracted. Frustration because of fruitless attempts to adapt will in many cases lead to a chronic stress response. For example, an animal that is cold and wants to go to a more comfortable spot but has nowhere to go in a pen with just one climate, will become restless and frustrated. In many of the current production systems for pigs, poultry, beef and veal, animals show symptoms of a chronic stress response, such as stereotypic behaviour, damaging behaviour directed to pen mates, elevated cortisol levels and depression. A chronic stress response may also suppress the immune function, leaving animals more exposed to opportunistic pathogens. Another cause of chronic stress is inhibiting species-specific behaviour, such as rooting or dust-bathing on a concrete floor.

At herd level

Disturbances at herd level that cause variation in the level of sustainability include variation in feed quality (storage, variation in raw material), wear and tear of equipment, corrosion, accumulation of dust and obnoxious gases in the air, pests (such as insects or rodents), a transport ban, a power cut, changing legislation, but also variation in individual requirements of animals managed as groups. Many of these challenges are dealt with according to the 'protect or intervene' approach although in some cases this is the only option.

5 http://www.oie.int/eng/maladies/en_classification.htm

Arable production

Soil degradation

High inputs of artificial fertilizers made crop production systems less dependent on the quality of the soil and the soil was therefore mainly seen as a substrate. The use of solely artificial fertilizer may lead to a reduced soil organic matter content, which plays a critical role in the maintenance of soil structure and water holding capacity. Intensive soil cultivation may aggravate the soil degradation process.

Emerging pest, weed and disease problems

The large-scale cultivation of monocrops may initiate pest and disease problems as insect pests can effectively track and colonise crops and diseases can spread fast in monocrops by plant to plant infection. The heavy use of fertilizers may make crops vulnerable for attack by insect herbivores and pathogens (Matson et al. 1997). Many agricultural pests, such as aphids, leafhoppers and planthoppers, have shown strong population increases in response to nitrogen fertilization. The use of broad-spectrum pesticides disrupts pest regulation by natural enemies and the development of resistance against chemical pesticides in insect herbivores, weeds and pathogens has become a serious problem (Clarke et al. 1997). For instance, insects and weeds often evolve resistance within one and two decades, respectively. Similarly, crop resistance to pathogens generally lasts only a couple of years.

The interrelation between arable and animal production

The paradigm underlying the Control Model also caused animal and arable production to become detached from each other. With the introduction of chemical fertilizers and the globalisation of the market for feedstuff, different agricultural sectors had the opportunity to maximize production independently. One of the effects of the disengagement of the arable and the animal sectors was that poultry and pig production could grow enormously without an associated arable sector for producing the feedstuff. This resulted in a huge surplus of manure. Meanwhile, the arable sector had grown accustomed to the use of chemical fertiliser, which at the time was considered to be much easier for precisely meeting the plant requirements at the right time. Manure was therefore only used for the limited amount of land that the poultry and pig farmers did possess, thus creating an environmental problem. Another problem introduced by the detachment of animal and arable production is quality and risk management of globally traded ingredients of animal feed.

Negative side-effects of the Control Model in animal and arable production

Toxic residues

Pesticides applied to arable fields may result in significant doses of pesticides reaching adjacent ecosystems via leaching or aerial drift, where it can have a strong impact on non-target organisms. Also abundant use of veterinary medication may lead to metabolic residues accumulating in the environment.

Loss of biodiversity

Scaling-up of field sizes, removal of non-crop habitats and large-scale monocropping have lead to simplified agro-ecosystems with only few and fragmented non-crop habitats left. Together with the frequent and intensive disturbances in crops, these developments have contributed to a rapid decline of biodiversity in rural landscapes (Benton et al. 2003). At the present time, most biodiversity in intensively used areas is concentrated in field edges and non-crop habitats. In animal production, the number of lines and breeds has decreased significantly after the process of intensification and scale-enlargement commenced. This is a direct consequence of the removal of local sources of variation, which made locally adapted populations redundant.

Loss of cultural diversity

With the introduction of production systems that were independent of the local context, local variation in customs, practices and production systems gradually disappeared. This has lead to an increasingly monotonous countryside, aggravated by the scale-enlargement. Pig and poultry production units generally make a dull and closed impression to the general public.

Lack of public support

With increasing biosecurity, animal production systems have become inaccessible for the general public. This makes people wonder what is going on. Many are also concerned about the above-mentioned problems and it is easy to blame the farming community.

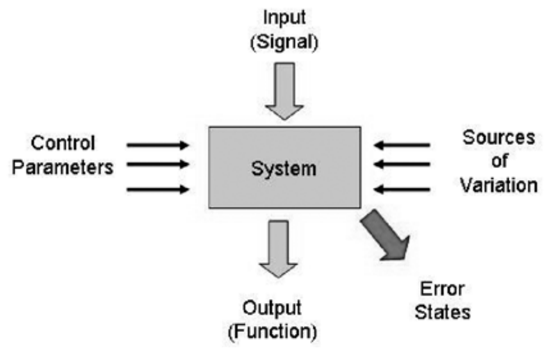
Adaptation model

The key element to the Adaptation Model is that systems at all levels are designed to reduce the consequences of sources of variation, rather than taking out the sources of variation. It is a matter of managing sources of variation where possible, and removing them where easy or necessary. In this way, robust cropping and animal production systems contribute to a stable and sustainable agricultural sector on the basis that a complete prevention of threats is not feasible.

Under the Adaptation Model, the design of production systems and processes is optimised for stable performance in the normal bandwidth of sources of variation. This means that financial income no longer is the optimisation criterion, but a stable and reasonable income is used as a precondition in the design process. In fact, some productivity is traded for stability.

For the design of a robust production system (Fig. 2) it is necessary to have a measure of the ideal function of the production system. Disturbances that one cannot or decide not to remove will result in a functioning that deviates from the ideal function. In addition, there are control parameters, of which some will have an impact on the level of functioning and others on the variation of functioning in the presence of disturbances. The concept of robust design is to use robust components and set control parameters in such a way that deviations from the ideal function caused by the present disturbances are minimal. This concept has been implemented for quality control in engineering cars and microchips ("Robust Engineering Design", "Robust Design", "Taguchi Methods", see Phadke, 1989; Dehnad, 1988; Taguchi, 2004).

Figure 2. Schematic representation of a production system



As an example, the system could be a production system with pigs. The input is feed. Sources of variation are seasonal changes in climate, presence of pathogenic micro-organisms, presence of an aggressive pen mate, etc. Control parameters (in the design process!) are stocking density, pen size and layout, building layout and distance between buildings, but also management procedures for weaning and moving pigs and changing feed. The deviation from the ideal function (the output) could be the total loss to anyone (pig, farmer, buyer, society) of a pig produced or it could be the loss of welfare to the pig.

Using robust components implies utilising intrinsic robustness mechanisms. For a discussion of biological robustness, see Kitano (2004). In animal production, these mechanisms include behavioural, physiological and immune responses at the animal level and a stable micro-flora at the herd level. Relying on these mechanisms does require confidence in the natural ability of animals to cope. Sometimes it is argued that our domestic animals are too far removed from their wild ancestors to be able to cope with natural stressors. However, several studies showed that pigs (Jensen, 1988; Stolba and Wood-Gush, 1989) and poultry (McBride et al., 1969; Wood-Gush et al., 1978) are very well able to live a natural life after being released into the wild or in a semi-natural enclosure.

For cropping systems, intrinsic robustness mechanisms exist at the level of the plant and the field or farm. Diversification at all levels is regarded as a promising strategy to safeguard food production with only limited dependence on agrochemicals. Diversified cropping systems may be less sensitive to invading weeds, pests and diseases for a number of reasons: a more efficient use of resources, a higher occupancy of niches, a more abundant and diversified community of natural enemies, less effective transmission of pathogens and more favourable structural and micro-climatic conditions, which together may reduce the impact of yield-reducing agents.

It must be stressed that stability of sustainability cannot be achieved by just using robust crops and animals. It will require a re-design of systems at many levels, from animal or crop, herd, production chain and sector to national and international arrangements in order to utilise robustness.

The key features of the Adaptation Model at the levels of individual animal or plant, crop, herd and production chain are:

1. Allow to cope where possible, but protect where necessary
2. Utilise intrinsic adaptation mechanisms, allow them to learn-by-doing and support them
3. Consider the possibility that fundamental re-design may be necessary

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Animal production

Infectious diseases

There are two main ways to avoid clinical disease symptoms (hence not including sub-clinical disease). Firstly, to avoid exposure of the animal to the pathogen and secondly, to avoid that infection results in clinical symptoms. The third way, which is to avoid that exposure results in

infection (e.g. genetic resistance to F18 E. coli in pigs), is too rare to be used as a general strategy. Under the Adaptation Model, it is a conscious decision whether one of the two or both are employed to minimise clinical disease. For some pathogens, there is no alternative option to avoiding exposure, as animals will be dead before they have mounted an immune response (e.g. highly virulent Asian Influenza strains) or because of international agreements (Diseases Notifiable to the OIE)3. In practice, it is probably best to start up with the highest health status that can be maintained for a considerable period of time.
As yet, there are no systems that are consciously optimised for avoiding that infection results in clinical disease. It requires that animals are prepared for exposure, in case it happens, and that the production system hamper pathogens spreading and replicating rapidly. The latter has consequences for density of animals, contact structure between animals, age structure of the population and management of microflora in the environment, among other things.
The ability of an animal to deal with infection depends on its genetic potential, its experience and, at the time of exposure, its physiological state and the support it gets for adaptation. Concerning general resistance to clinical disease, we should not expect large gains from breeding and selection. A good overview of what is possible and what not in poultry breeding is given in Muir and Aggrey (2003). Although there are examples that unbalanced genetic selection caused increased sensitivity to a specific pathogen and examples that selection against a specific pathogen was successful, there is no evidence that the genetic potential for immune-competence has deteriorated or is insufficient.
Building up experience may occur through low-level exposure under some form of protection, through which the immune system learns to mount an appropriate response. It has been suggested for this purpose to use vaccinations, keep animals in more natural social groups (weaning them at a later age), bring animals into well-controlled contact with non-pathogenic micro-organisms early in life, and manage the intestinal microflora by enriching diets with roughage and pre- and probiotics, in order to prepare animals for exposure (Van der Weijden and Schrijver, 2004). For some of these suggestions, however, there is only circumstantial evidence. A concerted approach is required to determine the best over-all strategy.
An appropriate response at the time of exposure also requires that the immune system is not suppressed through a chronic stress response, that the animal has sufficient metabolic resources available and that the environment supports an appropriate response, for example by providing a micro-climate with a higher temperature.

Non-infectious sources of variation

Situations of chronic stress should be avoided, not only to avoid immune-suppression, but also because they generally arise from a breach of welfare. This means that animals should be kept in an environment in which they can behave and adapt as the they require, including species-specific behaviour. The ability to adapt successfully again requires sufficient genetic potential, building up experience and getting the opportunity and resources to adapt. Optimising production systems and processes for building up experience and supporting adaptation is a new perspective and many questions are still unanswered. What is the best way to prepare animals for a dynamic environment? What role do social skills play and how can they be developed? What support is needed for successful adaptation?
Dealing with disturbances at herd level for minimal deviation from the target output (however defined) through the design will be a challenge. It requires that production systems are already in the design phase exposed to these disturbances. It also needs to be assessed what kind of disturbances in terms of incidence and seriousness should be included in a Robust Design approach.

Arable production

Soil health

Improving soil quality with an approach that focuses on a sustainable soil management is a major key for the Adaptation Model. Improving soil quality means improving physical, chemical and biological conditions of a soil for a stable crop growth. Sustainable soil management might be achieved through a site-specific approach, a sound crop rotation, good-management practices and fertilization including organic soil amendments. The use of animal and green manure, cover crops and reduced tilling may raise the organic matter content of soils and enhance the diversity of soil organisms. These features are associated with enhanced disease suppression, nitrogen-mineralization and a favourable soil structure. A healthy soil is therefore the basis for robust crop growth.

Plant/Field level

Yield stability can be obtained by the use of varieties that have specific traits that makes the crop less vulnerable to unfavourable conditions and yield reducing agents. For instance, varieties with a deeper rooting system are more tolerant to drought, a dense crop canopy improves the competitive potential of the crop and hairy leaves make the crop less attractive for aphids (Lammerts van Bueren et al. 2002). Diversification at the plant level may entail the breeding or genetic engineering of crops that are resistant to pathogens (e.g. Phytophthora infestans) or pests (e.g. crops that produce Bacillus thuringiensis toxin). The world-wide reduction in pesticide use by the use of Bt-corn and cotton are tremendous. However, if their deployment is to be sustainable, resistant crops must be used in conjunction with methods that promote natural occurring antagonists. Otherwise their effectiveness is prone to neutralization by resistance in the same manner as with pesticides. To date, there is considerable resistance towards the use of genetically modified organisms among the general public in the Netherlands. The use of genetically engineered crops with subtle changes, for instance crops containing resistance genes originating from related plant species, are likely to be less controversial. Diversification at the within-field level may involve agroforestry, multicrops, cover crops, variety mixtures, or beetle banks that act as sources of predators that may control pest populations. Good results have been obtained by the use of variety mixtures, resulting in a substantial reduction of pesticide use (e.g. Zhu et al. 2000). Although multicropping is common in the tropics, it is hardly used in the temperate zone because it requires careful selection of plant species, intensive and careful management and there is a lack of machinery tailored to harvest multiple crops grown at the same time in the same field. Precision agriculture may be used for local interventions with pesticides when yield reducing agents seem to go out of control. Diversification at the field level may involve the establishment of field margins, inclusion of fallow periods and crop rotation. Field margins may reduce drift of pesticides and may act as sources for natural enemies that may control pest densities in crops. However, in particular cases field margins have also been shown to support for pests. Careful selection of plant species is therefore essential to enhance the diversity of field margins, but without the stimulation of pests, weeds and diseases.

Farm/landscape level
Diversification at the farm or landscape level may involve the establishment of hedgerows and other semi-natural habitats and the re-introduction of arable-livestock systems. Arable-livestock systems allow favourable nutrient management (e.g. potential to close nutrient cycles at the farm level). Diversified landscapes composed of arable fields intermingled with natural habitats have in general a more abundant and diverse natural enemy community and often lower pest densities in crops (Thies and Tscharntke 1999). Many processes in pest and disease development act at spatial scales exceeding the farm scale. Farmers should therefore join forces for effective pest and disease management. An example of a project aiming at the diversification at higher spatial scales is the Functional Agro-biodiversity Project (2005) which aims to enhance biodiversity and suppress insect pests by the large-scale establishment of field margins in de Hoeksche Waard.

The interrelation between arable and animal production

In natural ecosystems synergistic interactions among plants and animals are common. Such interactions between plant and animal production may help both types of production to become more stable. Animal production may help to stabilise crop production through widening of crop rotation or grazing under-crops, such as grass-clover or lucerne. This may support soil health and weed suppression. Plant production may stabilise animal production through removing excess minerals and reducing disease burden in pig or poultry outdoor yards or by growing crops for animal feed at minimal cost. Plant and animal production could also mutually benefit from cooperation by optimally utilising the excess of manure from animal production systems. Another example is keeping poultry and sheep in orchards, where the trees provide shade, the poultry reduce the burden of harmful insects and the sheep reduce the development op fungi by eating weeds, grass and old leaves (Bloksma et al., 2002).

Impact on aspects of sustainability

It is evident that much more work is required before the impact of adopting the Adaptation Model on sustainability can be assessed accurately. Nevertheless, there is great potential when considering the definition by TransForum (see Introduction). With regard to profitability for an agricultural producer, productivity of the herd will reduce and the price per unit of product will reduce as well, unless the product fits a niche market. This means that the cost of production has to be reduced considerably, especially the fixed cost. However, there are already some promising examples (Heineken, 2004). With regard to product quality, there is a potential for product differentiation for niche markets (e.g. agricultural production methods that embrace local customs or heritage may be sold as regional products), but there is also a potential for producing uniform products for bulk markets with diverse production systems when farmers get used to optimising for minimum variation. The environmental burden may be lessened if the use of medication and chemical crop protection is reduced (e.g. reduced toxic residues in the environment) and the emission of nitrogen and phosphate is minimised. Concerning animal health & welfare, a well-prepared immune system in combination with a stable micro flora and an appropriate biosecurity may improve animal welfare through a reduction of clinical diseases symptoms. Allowing animals to adapt may reduce the undesirable side-effects of chronic stress. Allowing biodiversity of wildlife to increase will improve the attractiveness of the countryside (e.g. flowering plants in field margins are often appreciated by the general public). We anticipate that the above will have a positive impact on public support, especially when the positive contribution is also intuitively clear.

Towards sustainability even in adverse conditions

Our vision for agriculture in the future is one of an agriculture that is sustainable not just in ideal conditions, but in the entire bandwidth of normally occurring disturbances. This requires a shift in paradigm from the Control Model to the Adaptation Model.

Current situation
In the Netherlands, a move towards more sustainable animal production has already started. Support from the general public, impact on the environment and animal health and welfare are increasingly taken into account. Yet there is still a long way to go.
The primary strategy to improving sustainability, however, is largely based on the Control Model: solutions aim at protecting against sources of variation and require technical or human intervention. Examples from animal production are biosecurity as the single means of improving animal health and filters in the air outlet of pig and poultry sheds to reduce environmental pollution. The solutions need to be almost perfect as failure has potentially far-reaching consequences.

In animal production, the interest in aspects of the Adaptation Model is restricted to a number of non-veterinary scientists and a small number of predominantly organic farmers. Utilising inherent robustness of animals is therefore controversial. Many veterinarians and farmers consider inherent robustness to be irrelevant for existing production systems or lack the confidence to rely on it. The perception of the general public is that animals have lost inherent robustness because of continued genetic selection for production traits. Our view, however, is that existing production systems ignore inherent robustness and counteract any attempts of animals to deal with threats.

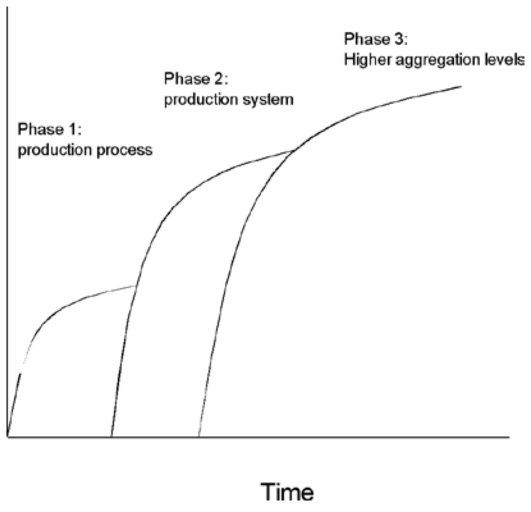
In crop production a gradual shift towards more sustainable production systems is also evident. Even though nearly all crop varieties used are developed for maximum yield under optimal conditions and some farmers still adopt practices associated with the control model (e.g. calendar sprays), there is an increasing interest in agricultural production systems that utilise internal self-regulation processes and are therefore less dependent on human intervention. For instance, integrated pest management (IPM) strategies are now widely used and farmers become more and more interested to use functional biodiversity to enhance the resilience and buffering capacity of the agro-ecosystem. In addition, organic farmers form a small group of front runners that develop cropping systems that are robust without dependency on agrochemicals.

Achieving the vision

A transition towards a more sustainable agriculture consists of many, largely autonomous processes. Small technological innovations may gather momentum if sufficient people take up the idea and develop it further, and if the conditions are right. If such innovations lead to changes at a higher aggregation level and to changes in perception, attitude and behaviour in society, then it has evolved into a system innovation.

The shift from the Control Model towards the Adaptive Model can be considered as a development process that involves three phases (Sterrenberg and Brandt 1996). The first phase involves changes in the production process. Amendment of the production process can be realised within the current production system and may entail a reduction of stocking densities or the shift from calendar sprays to spraying according to damage thresholds. Although such an altered production process can be implemented relatively quickly, the expected benefit resulting from these changes may be modest (Figure 3).

Figure 3. Improvements in sustainability per phase over time (Sterrenberg and Brandt 1996)



The second phase entails the transition of production systems. These changes often involve considerable investments, such as replacement of cage-housing of laying hens by an outdoor free-range housing system or the shift from conventional to organic farming systems, and can only be implemented in the longer term. The expected benefit, however, is likely to outweigh that of amendments in the production process.

The third phase contains changes at higher aggregation levels (e.g. regional level or production chain). Tuning production systems at larger spatial may result in the closure of nutrient cycles or the suppression of pests and diseases by habitat management and crop rotation. The implementation of these changes that exceed the system level require effective communication between farmers but hold promise of substantial benefits (Fig. 3).

Stumbling blocks

Legislation and regulations can easily stand in the way of the transition process. Pioneering farmers who want to implement new ideas, not seldom find themselves confronted with restrictions because of legislation and regulations. For example, if legislation about mineral losses in animal husbandry is implemented strictly, it is not possible to test and develop various alternative housing systems because the ammonia emission may be too high. Of course, a too high an ammonia emission is not acceptable for systems in practice, but legislation should not be restrictive to innovation in a promising direction.

Legislation that allows for making an exception for promising initiatives may be instrumental in stimulating the innovative potential of farmers. This requires effective communication

between policymakers of different disciplines and the agricultural sector. Also, a different approach in legislation and regulations may be helpful. Many regulations, such as the Dutch quality assurance for pig production (IKB), are at the level of the means, rather than the objectives. Instead of exactly prescribing how a farmer should do something, the regulations could provide a framework of only a few important preconditions within which a farmer has to achieve certain goals, for example a mortality below a certain maximum. In this way, general goals can still be achieved and farmers have more freedom for developing innovative solutions.
Another stumbling block is the organisational structure of many of the agricultural production chains. Firstly, there is a lack of trust between primary production and other links. Secondly, there is a concentration of power in links other than primary production, such as retailers, leaving primary production fragmented with virtually no power. The lack of trust is also an issue between primary production and the various governments.

Research agenda

1. Raising awareness
Technological innovations based on the Adaptation Model will not be successful unless an increasing number of people adopt the Adaptation Model as a conceptual framework. The Adaptation Model must have sufficient critical mass in order to progress. It means that research should raise the awareness among farmers, specialists, scientists, the supplying and processing industry and the general public of the differences between the two paradigms.
Projects in this area could demonstrate the process of interactively designing for a normal bandwidth in a given context. This could be done at three levels: designing new production processes within existing systems, designing new production systems and processes, and designing new economic structures, production systems and production processes. It requires an interdisciplinary and interactive design approach to develop stimulating and thought-provoking prototypes. The objective of such demonstration projects is not to develop ready-made solutions, but to change the perspective for innovations.
A second issue in this area is perception and management of risk. Especially the notion of a zero-risk is a potential time bomb for the farmers' profitability and the consumers' confidence. The change in risk perception is necessary to build the trust of the general public, and to make the various parties involved prepared to make an effort.
Related to this is also the problem of allocation of costs of calamities, especially when the consequences increase with a reducing risk. Under the Control Model, the society always paid for the costs of for example environmental pollution (clean water management) through taxes and not via more expensive products. In this way, the true costs of the current production system are not visible (Kalverkamp and Van Hoytema, 1989).

2. Designing for robustness
The methodology required for developing inherent robust agricultural production processes and systems is not available. The theory, however, exists and has been developed for industrial production processes (Robust Design). This largely statistical theory needs to be changed and adapted for agricultural production systems and tested for suitability. Following the adaptation of the general methodology for agriculture, it would be helpful to have a simple protocol or tool that a farmer can use to evaluate alternative practices for impact on variability. This needs to be developed and disseminated in practice.
Additional work is also needed to further develop system approaches to achieve more inherently robust production systems of agricultural products. Kitano (2004) argued that robustness is a fundamental feature of evolvable complex systems. Special emphasis is therefore required for self-learning systems at all levels, that evolve through learning-by-doing.

For new systems to contribute to a more sustainable agriculture, it is necessary that there is a continuous reflection on presuppositions and possible negative side-effects and partitioning issues that come with it (Beck, 1992). This requires a much stronger interaction between social and technical sciences and a substantial involvement of society in the design process, for example through citizen groups.

3. Technical research

The change from the Control Model to the Adaptation Model also raises many technical questions. For example in animal production, there are still many unanswered questions regarding optimum utilisation of the animal's ability to adapt through genetic selection, training and support. The answers may also vary for the various classes of non-zoonotic and zoonotic pathogens and non-infectious environmental stressors. Another issue is the avoiding of chronic stress. Is it possible to apply the current knowledge to existing production systems in the short term and design improved systems in the longer term? A third issue is avoiding of damaging behaviour to pen mates, in case a chronic stress response inadvertently occurs. Managing the micro-flora to control pathogenic micro-organisms and keeping it stable may be another promising area.

In crop production, robust crop varieties are currently not available. Breeding programs may select varieties that attain good yields under a wide range of conditions. Further, multi-cropping systems may solve much of current problems concerning yield reducing agents, but are not used in practice. The identification of well-balanced crop combinations and development of machinery to harvest multiple crops in the same field may make mixed cropping systems feasible for practice. Finally, there is little knowledge of how the diversity of soil biota, extra-field vegetation and natural habitats may enhance crop production. In particular, effects of incentives at larger scales (e.g. cooperation between farmers) have received little attention.

With regard to integrated cropping and livestock production systems, there is a need for developing and testing one or two appealing concepts for fully utilising the synergy for achieving a sustainable agriculture. The objective would be to stimulate the development of novel ideas in practice.

4. Development and dissemination of knowledge

Under the Adaptation Model, local sources of variation are taken into account in the design. This means that the result is a more diverse and context-based type of agriculture. It also means that the concept of centrally developing innovations and disseminating them into the commercial practice has become void. A different concept for knowledge development and dissemination is required. The project 'Netwerken in de Veehouderij'[6] in 2004/2005 provided a lot of valuable experience for an alternative concept, which would be quite appropriate for working with the Adaptation Model.

6 http://www.verantwoordeveehouderij.nl/index.asp

Critical in a more context-based agriculture is the ability of a farmer to develop the best production system for the specific context of the farm. Farmers learn by observing, sharing experience and combining forces to get answers to shared problems. Input from scientists is needed for a broader development of concepts, for other contexts and in-depth knowledge of underlying processes. Hence, projects should aim at teaching farmers to observe and researchers to listen.

As a consequence, dissemination of knowledge shifts to a large extent from dissemination of solutions to dissemination of ways to solve context-specific issues. This requires a different way of technical support. In the new situation, solutions are owned by innovative farmers, who may not be interested in providing their solutions to the others, except if they get something in return, for example in a farmers' study group.

The Adaptation Model does not stop at the farm gate, but affects the entire production chain. More study is needed to obtain an organisational structure that builds mutual trust and creates an environment in which innovations arise and prosper.

Conclusions

Many of the current problems in agriculture related to sustainability, seem to be associated with the way how agriculture attempts to achieve stability. Developing and utilising intrinsic robustness of animals and cropping systems, instead of solely relying on protection and intervention, seems to be a major step in the direction of an agriculture that is sustainable in the entire bandwidth of normal conditions. This requires a raising of awareness among all parties involved, development of methodology, fundamental and applied technical research and a change in the way that knowledge is developed and disseminated.

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