Innovation born of Integration

Moving towards sustainable production of animal-source food

Prof. dr *ir*. Imke J.M. de Boer

Inaugural lecture upon taking up the post of Professor of
Animal Production Systems at Wageningen University
on 11 October 2012

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Rector Magnificus, family, friends, colleagues, ladies and gentlemen,

While thinking about the content of this inaugural lecture, the following song came to my mind: *Wim Sonneveld, Het Dorp*. This song triggers a nostalgic feeling, a feeling that agriculture was better in former times than today. I wondered, however, if this feeling was not misleading: was livestock production really better, or if you prefer, more sustainable in former times? At the end of my lecture, I will come back to this question.

Let me start by sharing some thoughts about sustainable development with you. A definition of sustainable development used commonly in agricultural research is the one from the Brundtland report: sustainable development is "a development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). This definition contains two key concepts of sustainable development (further referred to as sustainability): needs and limitations. To survive, people across the world need, for example, food, housing, clothing, education, and health care. To fulfill these needs, we are limited by the state of the technology, the societal organization, and the carrying capacity of the earth. The Brundtland commission (named after its chair Gro Harlem Brundtland), therefore, recognized the three domains of sustainability that we currently acknowledge: the domains of people, profit, and planet or, in other words, social, economic and environmental sustainability. In the agricultural field, social sustainability ensures that production systems, such as a farm, are socially accepted. Social acceptability implies that a production system should be embedded in its social cultural context, should be respectful towards humans and animals, and should contribute to equitable management of resources. Acceptance of systems differs across regions of the world, because of differences, for example, in cultural values or prosperity. Social sustainability includes issues of food security, food safety, human health risks, labor circumstances, animal welfare, and equity. Economic sustainability implies balancing expenditures and revenues so that a system can sustain, and includes issues of profitability, volatility and employability. Environmental sustainability implies living within the carrying capacity of the earth or, in other words, using natural resources in economies or societies at a rate not exceeding their regenerative and their absorptive capacity, and includes issues of climate change, acidification, depletion of fossil fuels or biodiversity loss.

Global assessment reports, such as Livestock's Long Shadow (Steinfeld et al. 2006), demonstrate clearly that current animal production levels pose severe pressure on the environment via their emissions to air, water, and soil. The world's livestock sector significantly contributes, for example, to climate change, acidification, water pollution, and biodiversity loss. The livestock sector also competes increasingly for scarce resources, such as land, water, fossil energy, and fossil phosphorus. The current sector is responsible for about 15% of the global anthropogenic emissions of greenhouse gases (GHG; Steinfeld 2012), whereas it uses about 70% of all agricultural land and represents about 8% of the global water withdrawals (Steinfeld et al. 2006). The way we keep our livestock, furthermore, is a point of discussion in Europe and, increasingly, across the world. Concerns arise about, for example, the welfare of our production animals, the size of our farms, and the threats for human health, because of zoonotic diseases and antibiotic resistance in humans arising from, for example, use of antibiotics in livestock.

We still expect an increase in the demand for animal products, because of growth of the global human population, especially in developing countries, growing incomes and urbanization. The demand for animal products is expected to double by 2050 (FAO 2009; Rae 1998). Without major changes, therefore, the above described environmental and social concerns about the livestock sector will only increase further.

At this moment, decision-making regarding sustainable animal production is hindered by the complexity and uncertainty of the impact on sustainability of, e.g., a new technology, a new farm design or a new feeding strategy; in other words, the impact of an innovation on sustainability. A transparent societal and political debate about future options and limitations of sustainable animal production systems requires a clear understanding of the impact of *innovations* on the diverse issues of sustainability.

My aim for Animal Production Systems (APS) group is to explore the multi-dimensional, and sometimes conflicting, consequences of innovations in livestock systems across the world (trade-offs and synergies), with a special focus on their impact on the *environment* (i.e. on efficient use of resources and on emissions to air, water or soil), their impact on *animal welfare* (i.e. on animal behavior, animal health) and their impact on the livelihood of people (i.e. on farm income, volatility, employability, and food security). Innovations to be explored can originate from diverse disciplines, such as feeding, breeding or farm technology, but they can also arise from our understanding and generation of knowledge resulting from the integrated system analysis, such as production of milk and meat from grass-fed dual purpose breeds.

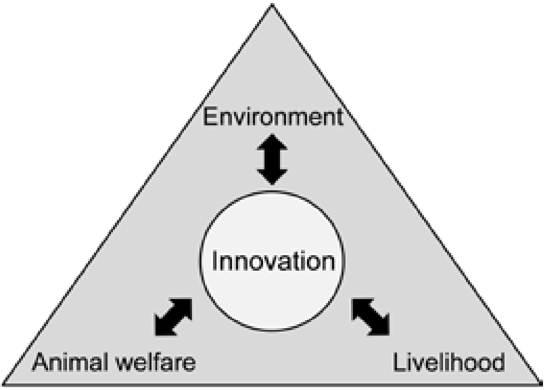

Figure 1. Focus of APS integrated system analysis.

In the following sections, I will provide some examples to demonstrate how we try to assess the consequences of an innovation on the efficiency of using resources, on emissions to the environment, on animal welfare and on the livelihood of people.

Environmental impact assessment of an innovation

Environmental sustainability implies that natural resources (e.g. land, fossil energy, fossil phosphorus, or water) are used in economies or societies at a rate not exceeding their regenerative and their absorptive capacity. Not exceeding the regenerative capacity implies compensating the reduction of the stock of a resource, e.g. crude oil or fossil phosphorus, by a substitute that can provide equivalent functions, e.g. provider of energy or nutrients. In this way, the functions of natural resources are assumed to remain available, completely and indefinitely (Hueting and Reijnders 1998). Not exceeding the absorptive capacity requires defining this capacity for water bodies, soils and air. In some cases, we have quite some knowledge about the neutralizing capacity of natural soils, for example, which enable an accurate estimation of the admissible environmental burden due to acid rain (Reijnders 1996). In other cases, however, we have insufficient knowledge to make firm pronouncements. Based on the best available global circulation models, for example, it can be calculated that worldwide emissions of carbon dioxide must be reduced drastically to achieve stabilization of the global warming process, but an exact percentage cannot be given. Stating if a product is produced environmentally sound, therefore, appears difficult. We can, however, assess changes in efficiency of using natural resources and in the amount of pollutants emitted to the environment due to introduction of an innovation, and, as such, determine its environmental impact. This will be the point of origin in our environmental impact assessments.

Intermezzo – Two examples of natural resource use in the past

The first example is near home, and originates in the 17th century. Jan Bieleman studied the evolution of farming systems in the Dutch province of Drenthe between 1600 and 1910, a pre-statistical era (Bieleman 2009). He based his analysis, therefore, on regional registrations of taxations. Between 1622 and 1802, a farmer had to pay one *stuiver* (1/20 of a guilder) for every sheep 'wesende jarigh ofte daer de scheere overgegaen is' (of one year old or which has been sheared once). This tax registration allowed a reconstruction of the evolution of keeping sheep in Drenthe. In the early 17th century the sheep stock expanded rapidly, induced by an increasing demand for wool. Bieleman also noticed that around 1650 farmers started complaining that their common land had turned into a desert, and that their open fields and villages were largely overblown with drifting sand (i.e. "stuifzanden"). In his research Bieleman illustrated that the growing demand for wool in the early 17th century resulted in unsustainable use of common land, and finally in local soil degradation and formation of drifting sands. He described a classical example of the "tragedy of the commons" (Hardin 1968).

The second example of the "tragedy of the commons" is global and also originates in the 17th century. It demonstrates overexploitation of worlds' lakes and oceans. Overexploitation of large vertebrates and shellfish appears to be the first major human disturbance to many coastal ecosystems (Jackson et al. 2001). An example of overexploitation is industrial whaling, which significantly reduced the global whale population. Around 1670 the whale population around Spitsbergen was already so low that whalers moved to other grounds. Finally, in 1986 the International Whaling Committee proposed a temporary ban on whaling, except for aboriginal subsistence whaling or scientific purposes. This ban, however, is not recognized by Norway, Iceland or Japan.

To identify livestock products or innovations that can reduce the environmental impact substantially, we use life cycle assessment (LCA). LCA is a well-established and standard method to evaluate the use of resources and emission of pollutants during the life cycle of a product (ISO 14040, 1997; ISO 14041, 1998; ISO 14042, 2000a; ISO 14043, 2000b). Let me explain why I think that a life cycle approach, or if you prefer a chain analysis, is essential to identify environmentally-friendly innovations. In Figure 2 you see the production chain of Dutch milk. Dutch milk is produced on a dairy farm.

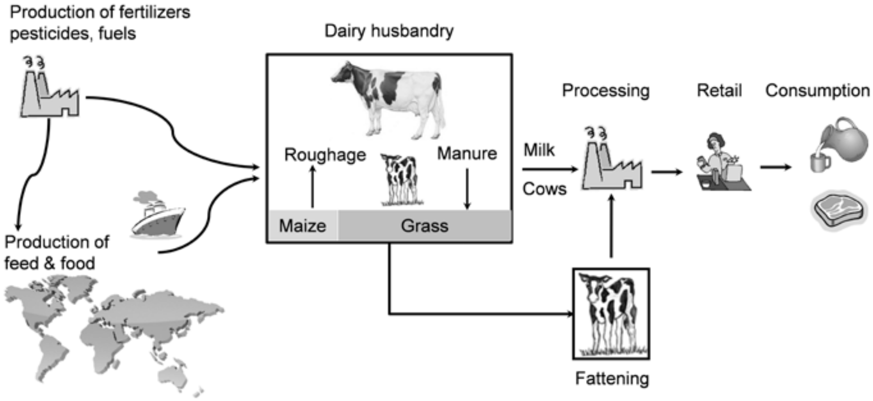

Figure 2. Important stages in the milk production chain (black arrows represent material flows).

A Dutch dairy farmer on sandy soils, for example, owns an average of 75 cows and 45 ha of grass and maize land. These 75 cows produce about 26 liters of milk a day. After milk leaves the farm-gate, it is processed, packed and, finally, transported to supermarkets, where it is stored until consumers buy it. Culling of cows also results in production of meat. Not all of you might be aware that to produce milk, a cow must give birth to a calf, generally every year. Not all new-born calves, especially not bull calves, are needed to maintain the milk-producing herd. Surplus calves, therefore, are fattened to produce meat. To produce 26 liters of milk a day, cows need feed. Part of this feed, such as maize silage or grass silage, is produced on the farm itself. The majority of Dutch cows are allowed to graze during summer and hence, consume fresh grass. To produce roughage on-farm, a farmer not only uses manure of cows, but also purchases synthetic fertilizer, pesticides, and diesel fuel. To fulfill the nutritional requirements of our high-yielding cows, Dutch farmers purchase additional feed ingredients, which can originate from all over the world, requiring transport over land and water. During the cultivation of purchased feed ingredients, synthetic fertilizers, pesticides, fossil energy and fossil phosphorus are also used. Moreover, production of soybean meal, for example, is associated with deforestation. The different stages along the milk production chain are interconnected, and a proper evaluation of an innovation includes those stages along the milk production chain that are affected by its introduction. Let's consider an example regarding emission of greenhouse gases.

The livestock sector contributes to climate change through emission of three major greenhouse gases (GHGs), i.e. carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). In dairy farming, especially CH_4 emission from enteric fermentation is important. Several studies explored the potential of changing the cow's diet to reduce enteric CH_4 emission (Ellis et al. 2008; Grainger and Beauchemin 2011). A feeding strategy with potential to reduce enteric CH_4 emission, for example, is replacing grass silage with maize silage in a cow's diet (Mills et al. 2001; Beauchemin et al. 2008). At the animal level, this is a promising strategy to reduce GHG emissions (Dijkstra et al. 2011). Literature, however, shows that dietary manipulation changes not only enteric CH_4 emissions, but also manure composition, and hence N_2O emissions from storage and application of manure (Chianeese et al. 2009; Kebreab et al. 2010). Replacing grass silage with maize silage, furthermore, might change the farm plan, i.e., part of the grassland will be ploughed for maize land. Ploughing grassland for maize land results in CO_2 and N_2O emissions, due to a change in levels of soil carbon (C) and nitrogen (N) (Vellinga and Hoving 2011; Van Middelaar et al. 2012a). Cultivating maize instead of grass, moreover, requires different fertilization and land management, changing N_2O emissions from crop cultivation and emissions related to production of fertilizers (Schils et al. 2005; Basset-Mens et al. 2009). Finally, a change in roughage composition might affect the amount and type of purchased feed ingredients.

We, therefore, evaluated effects of replacing fresh grass and grass silage with maize silage on GHG emissions at three interdependent hierarchical levels, i.e. animal, farm, and chain levels (Van Middelaar et al. 2012b). First, we used linear programming (maximizing farm income) to define an average Dutch dairy farm on sandy soils (i.e. reference situation). Second, we combined mechanistic modeling of enteric fermentation and life cycle assessment to quantify GHG emissions at all levels. Third, we used linear programming to determine a new farm plan, while the intake of maize silage was increased with 1 kg dry matter per cow per day compared to the reference situation, at the expense of grass or grass silage (i.e. feeding strategy). Fourth, we compared GHG emissions of this strategy with the reference situation. We analyzed this feeding strategy for an average farm (13,430 kg milk/ha) and a more intensive farm (14,788 kg milk/ha).

At animal level, the strategy reduced emissions by 10.8 kg CO_2-equivalants (CO_2-e: unit of summed greenhouse gas emission) per ton standardized milk (i.e. 2.6%), implying an immediate effect on GHG emissions. At farm level, however, analysis revealed that it was not possible to implement the strategy for the average Dutch dairy farm because of current EU regulations. For the intensive farm, it was possible to implement the strategy, which resulted in a reduction of annual emissions of 15.8 kg CO_2-e per ton standardized milk (i.e. 2.3%). The ploughing of grassland for maize land, however, resulted in non-recurrent emissions of 913 kg CO_2-e per ton milk. From a farm perspective, therefore, the carbon payback time is 58 years. At chain level, annual emission reduction was 19.1 kg CO_2-e per ton milk (i.e. 2.1%), and the carbon payback time was 48 years. Our results show that the potential to reduce GHG emissions by a feeding strategy can be different at the animal, the farm or the chain level, and they demonstrate the importance of a life cycle assessment of options to mitigate GHG emissions.

Using an LCA approach, we explore fundamental questions such as *"do we need intensive livestock systems to feed the world in order to minimize the impact on the environment?"* (De Boer and Udo 2010), *"does increasing annual milk yield per cow reduce GHG emissions* (Zehetmeier et al. 2012; Flysjö et al. 2012)" or *"which type of animal protein can be produced with the lowest environmental impact?"* (De Vries and De Boer 2010; Oonincx and De Boer 2012). Answers to these questions, apparently, are not as straight forward as most people think or would like. Let me demonstrate the complexity of answering these questions.

To answer the question *"do we need intensive livestock systems to feed the world in order to minimize the impact on the environment?"*, I use LCA results of a comparison between conventional and organic milk production. These results show that organic milk production has a lower local environmental impact (i.e. eutrophication potential per kg milk and per ha) and a lower or similar global environmental impact (i.e. fossil energy use or global warming potential per kg milk) but makes less efficient use of land than conventional milk production (Thomassen et al. 2008). We observed, therefore, a trade-off between efficiency of land use and environmental impact.
The answer to our question, therefore, is location specific.

In areas of the world where land is abundantly available, organic milk production might be more favorable than conventional milk production. In Denmark, for example, population density is about one-third that in the Netherlands, and percentage of milk produced organically is about four times higher. In areas of the world with a high human population density, and consequently a high pressure on available land, conventional milk production might remain favorable. In case of conventional milk production, however, we need to limit the local environmental impact by, for example, environmental legislation (NEC directives, Nitrate Directives), de-clustering, efficient crop fertilization, or technological innovations.

Processing manure to produce synthetic fertilizer (i.e. a combination of separation and dewatering of the liquid fraction), for example, is often mentioned as a technical innovation to reduce the local environmental impact of intensive livestock systems. LCA results (De Vries et al. 2012a) show that processing of dairy cattle manure to produce synthetic fertilizer reduces the impact on climate change (global impact), especially when combined with anaerobic digestion of the solid fraction. Processing, however, increases fossil fuel requirement (global impact), particular matter formation (proxy for odor nuisance and, therefore local impact) and terrestrial acidification potential (local impact), but does not alter eutrophication potential (local impact). Within current EU regulation, therefore, such manure processing does not contribute to a reduction of local environmental impact (De Vries et al. 2012a). Compared to the above described manure processing, primary segregation of urine and faeces (i.e. segregation in the stable) has a greater potential to reduce the environmental impact (De Vries et al. 2012b). Primary segregation reduces climate change (global impact), terrestrial acidification and particular matter formation (local impacts), but increases potential eutrophication losses due to increased nitrogen values of manure. To limit local eutrophication, therefore, we need to combine primary segregation with efficient crop fertilization.

To answer the question *"does increasing annual milk yield per cow reduce GHG emissions?*, I point to an FAO study that quantified emission of greenhouse gases along the life cycle of milk production in many countries across the world (FAO 2010). They plotted emission of GHGs per kg of standardized milk against the annual milk production per cow (Figure 3). Emission of GHGs declined exponentially as annual milk production increased. Research indeed showed that if one is able to use feed more efficiently (i.e. produce more milk with the same amount of feed or use less feed to produce the same amount of milk), GHGs per kg milk produced is reduced (Thomassen et al. 2009).

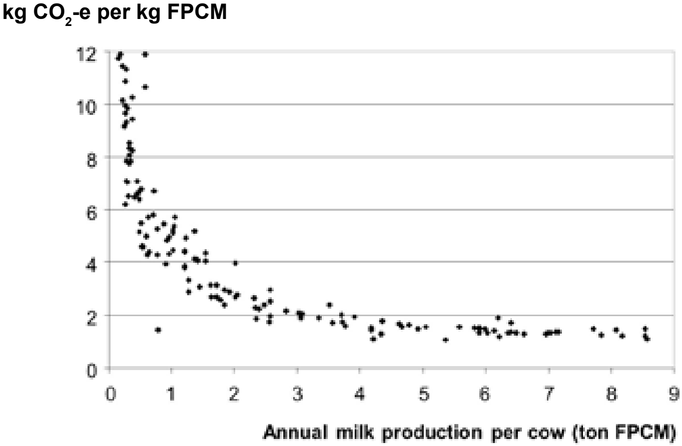

Figure 3. Relation between kg CO$_2$-equivalents (CO$_2$-e: measure of greenhouse gas emission) per kg fat-and-protein corrected milk (FPCM) and annual milk production per cow (in ton FPCM) (source: FAO 2010).

Can we directly compare smallholder systems in which cows produce 500 kg of milk annually with specialized systems in which cows produce 7000 to 8000 kg? Cows in many smallholder systems in developing countries generally are not kept to produce milk or meat, but they have important other functions, such as to provide manure and draught power for crop production, or to function as capital asset. Bosman et al. (1997) developed a conceptual approach to quantify the various functions of livestock in smallholder systems in the developing world in economic terms. If one allocates total GHG emissions of a smallholder farm to various functions of the animals, based on their relative economic value, GHG emissions per kg of milk produced are not that different between a specialized, intensive production system and a smallholder system. This does imply, however, that the capital asset function of smallholders contributes to climate change.

Similarly, Zehetmeier et al. (2012) compared GHG emissions per kg of milk for high-producing Holstein Friesians cows with emissions for moderate-producing Fleckvieh cows. When considering milk production of dairy systems alone, GHG emissions were lower for high-producing Holstein Friesians than for moderate-producing Fleckvieh cows. When considering milk and meat production of dairy systems, however, GHG emissions were higher for high-producing Holstein Friesians than for moderate-producing Fleckvieh cows. The answer to the question *"does increasing annual milk yield per cow reduce GHG emissions?"*, therefore, depends on the definition of your system.

To answer the question *"which type of animal protein can be produced with the lowest environmental impact?"*, we first reviewed the life-cycle impacts of various livestock products, such as beef, pork, chicken, milk, and eggs (De Vries and De Boer 2010). Production of 1 kg of beef protein used the most land and energy and had the greatest global warming potential (GWP), followed by production of 1 kg of pork protein and 1 kg of chicken protein. Results for land use are in Figure 4. Differences in life-cycle impacts (land use, fossil energy use, and GHG emissions) among pork, chicken, and beef products can be explained mainly by three factors: differences in feed efficiency, differences in enteric CH_4 emission, and differences in reproduction rates. No consistent differences were observed in life-cycle impacts between protein from milk and protein from chicken, pork or eggs.

Based on this review, we could propose to replace consumption of red meat with consumption of white meat. Compared with diets of ruminants, however, diets of pigs and poultry contain relatively more products, such as cereals, that humans could consume directly (Vellinga et al. 2008; Wilkinson 2011). Direct consumption of these cereals by humans is ecologically more efficient than consumption of meat produced by animals fed with these cereals, because most of the energy is lost during conversion from plant to animal product (Goodland 1997). Environmental consequences of the competition between humans and animals for land required to cultivate cereals are not incorporated in current LCAs of livestock products (Garnett 2009).

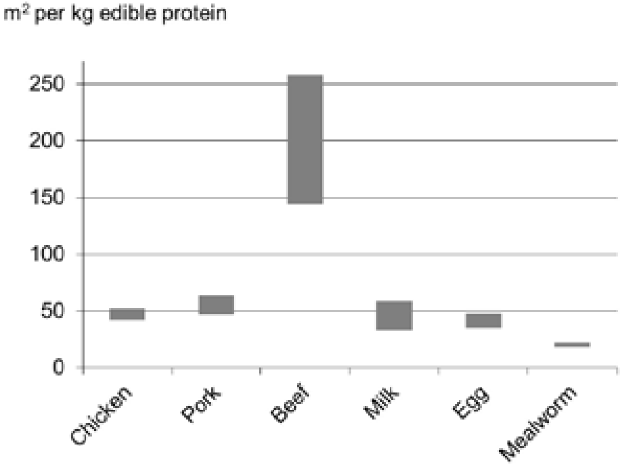

Figure 4. Range in land use (m²) per kg of protein edible for humans (Source: De Vries and De Boer 2010; Oonincx and De Boer 2012).

One way to gain insight into this competition for land between humans and animals is to compute energy and protein conversion ratios. These conversion ratios represent the amount of energy or protein in animal feed that is potentially edible for humans over the amount of energy or protein in the animal product that is edible for humans (see Table 1).

Table 1. Energy and protein conversion ratios (ECR and PCR) for various livestock products in the United Kingdom in 2008/2009 (Wilkinson 2011); ECR is edible MJ in animal feed/edible MJ in animal product, whereas PCR is kg edible CP (Crude Protein) in animal feed/kg edible protein in animal product.

Product	**ECR**	**PCR**
Milk	0.47	0.71
Upland-suckler beef	1.9	0.92
Lowland-suckler beef	4.2	2.0
Cereal beef	6.2	3.0
Pork	6.3	2.6
Chicken	3.3	2.1
Egg	3.6	2.3

Conversion ratios generally were > 1.0, except for milk, and, in the case of protein, for upland-suckler beef. Ratios above 1 are unsustainable because animals produce less edible energy or protein than they consume. Sustainable ratios below 1.0 may be possible by replacing feed edible for humans with co-products from crop cultivation or the food-industry that are not edible for humans, or, for example, by increasing efficiency of grass use in livestock production. In cooperation with Wageningen UR Livestock Research, therefore, we invested in a PhD project in which we explore the potential of pigs to produce environmentally-friendly pork while consuming mainly co-products not edible for humans.

Conversion ratios presented above, however, do not yet include the fact that, for example, grass fed to dairy cows can be produced on land suitable for cultivation of human food crops. We also invested in a PhD project, therefore, in which we combine LCA and land-use optimization models to explore appropriate strategies to fulfill human demands for animal protein in specific agro-ecological environments.

What about eating other types of animal protein, such as protein from insects: e.g. grasshoppers or mealworms? Dennis Oonincx and I recently performed an LCA of mealworms as a source of animal protein, based on data from a commercial producer of mealworms. The energy use for current mealworm production is greater than for milk or chicken, and similar to pork and beef. Mealworms, when considered as a source of animal protein, produce less GHGs and require less land, than poultry, pigs, or cattle. With availability of land being the most stringent limitation in sustainably feeding the world's population, this study clearly shows that mealworm might be considered as an environmentally friendly alternative to milk, chicken, pork, and beef as a source of animal protein (Oonincx and De Boer 2012). This eating habit might also contribute to my next issue to be addressed, i.e. animal welfare.

Synergies and trade-offs with animal welfare

The way we produce animal-source food affects not only the surrounding environment, but also the welfare of the animals. Sustainable food production is not just a matter of environmental or economic efficiency, but it implies respect towards animals. Attention for animal welfare is highly variable across countries, because of differences in, for example, cultural values or prosperity. Producing with respect towards animals is an important issue in Europe, and, increasingly, across the world. As I stated at the beginning of my lecture, my aim for APS is to gain insight into trade-offs and synergies of innovations between the impact on environment and the impact on animal welfare. In our group, we explore animal welfare from the perspective of natural sciences, which might differ from the perspective citizens have about animal welfare.

As with the definition of sustainability, many definitions of animal welfare exist. Although we recognize the complexity of defining animal welfare and the limitations of any definition, the so-called "five freedoms" cover the animal's basic needs, and can be used as an adequate and appropriate working basis to assess animal welfare: freedom from hunger and thirst; freedom from discomfort; freedom from pain, injury, or disease; freedom to express normal behavior; and freedom from fear and distress (FAWC 1992). These five freedoms are the point of origin for our welfare assessments.

Intermezzo – Two examples of animal welfare in the past
As explained previously, not all new-born calves, especially not bull calves, are needed to maintain the milk-producing herd. This fact, in combination with the fact that for many years Europe had an excess of milk products, resulted in a system where veal calves were fattened on predominantly milk replacer, producing meat with a pale color. These calves were traditionally housed individually in small crates. Veal calves in this housing and fattening system consistently showed a range of serious behavioral and health problems (Wiepkema et al. 1987; Fraser and Broom 1990; Veissier et al. 1998). Deficiency of roughage, little space, and social deprivation are causes of reduced welfare (Van Putten and Elshof 1987; Ketelaar - De Lauwere and Smits 1989; Veissier et al. 1997). To improve the welfare of veal calves, housing calves in groups and providing solid feed was made compulsory in the European Union (EU 1997a; 1997b). Similarly, other housing systems resulting in impaired animal welfare, such as battery cages for laying hens, are currently prohibited in the European Union (EU 1999) and, for example, in Bhutan.

One of the 'five freedoms' that cover the animal's basic needs is: freedom from pain, injury, or disease. In developed countries, major infectious diseases such as Rinderpest or Pleuropneumonia were either effectively controlled or eradicated between the latter part of the 19th century and the middle of the 20th century. Effective control of major infectious diseases was based on techniques of the microbial revolution (prevention, eradication, immunization, antibiotics) and older techniques (quarantine, import restrictions, hygiene, slaughter), and allowed an increase in animal numbers and animal productivity. This intensification of animal production, however, was accompanied with new animal health problems (Thrusfield 2007).

To identify trade-offs and synergies of innovations between the impact on the environment and the impact on animal welfare, we use three approaches: modeling; experimental research and analysis of data from commercial farms.

An example of modeling is a comparison of LCAs of existing egg-production systems that are expected to vary in hen welfare. Dekker and colleagues assessed life-cycle impacts for the battery-cage system, which is banned from 2012, and three loose-housing systems, which are expected to enhance hen welfare compared with the battery-cage system: a barn system, a free-range system and an organic egg-production system (Dekker et al. 2011). They showed that current loose-housing systems resulted in higher emissions of GHGs, higher land occupation and a higher acidification potential per kg of egg produced than the battery-cage system. If the total consumption of eggs does not change in 2012, then total emissions of greenhouse and acidifying gases, and land use from European egg production will increase, because of the ban on the cage system. To improve hen welfare, while maintaining or reducing the ecological impact of egg production, therefore, we need to reduce our egg consumption and/or to improve the ecological impact of loose-housing systems. Dekker (2012) identified key parameters to improve the ecological impact of loose-housing systems: improving feed conversion ratio, reducing nitrogen excretion of hens, improving hen housing (from single-tier to multi-tier housing), changing diet (i.e. maximizing co-products and eco-efficient feed ingredients), and redesigning the outdoor run.

Another example of modeling is directed at exploring relations among sustainability impacts in novel, not-yet-existing farm designs. We believe that modeling of animal behavior, using for example an agent-based approach, allows exploration of impacts of novel, not-yet-existing farm designs on environment, animal welfare and costs. The IPOP-theme "Complex Adaptive Systems" enables us to invest in this innovative modeling approach to explore relations among impacts on environment, welfare and costs of novel farm designs.

An example of experimental research is the so-called "veal calf project". This interdisciplinary project is a collaboration among the Animal Nutrition Group, the Business Economics Group, Livestock Research and our group. As I explained in my intermezzo, housing calves in groups and providing solid feed is compulsory in the European Union nowadays. Veal calves should be fed a minimum of 50 to 250 g of "fibrous feed" a day from 8 to 20 weeks of age (EU 1997b). Research, however, showed that these amounts are insufficient in preventing the development of abnormal oral behaviors, such as tongue playing and rolling, and health problems (Matiello et al. 2002; Morisse et al. 1999). These health problems currently limit improvements in calf welfare and limit economic benefits that could be reached by increasing the roughage component in veal-calf diets. In this interdisciplinary project, we aim to develop novel roughage-based feeding strategies for calves that will respond better to their behavioral needs, and circumvent and alleviate health problems. Ideally, these strategies should also be economically beneficial and ecologically sound. First results showed that increasing the solid-feed supplement to milk replacer decreased abnormal oral behaviors and increased rumination time. Furthermore, the results suggest that levels of solid feed should not remain constant, but instead should increase with age if higher rumination time is to be maintained (Webb et al. 2012). Increasing solid feed also improved nitrogen uptake by enabling urea recycling through improved rumen development. This means that calves fed solid feed were more efficient in their use of feed for growth (Berends et al. 2012). Replacing some milk replacer with solid feed, moreover, decreased overall costs of feeding, without reducing performance of calves and thus has an economic benefit. First LCA results, however, show that adding solid feed to the diet of calves, for example, increases greenhouse gas emissions along the chain, which is another finding that points to a trade-off between impacts on environment and animal welfare.

Frontier analysis of LCA and welfare scores is an example of data analysis of commercial farms. Frontier analysis of farm data offers the potential to uncover the relation between LCA and welfare scores among farms, and to benchmark the performance of individual commercial farms against a frontier of best practices (Huppes and Ishikawa 2005; Figure 5). Benchmarking of individuals farms allows identification of feasible innovations or management practices that improve welfare at a given LCA score, or the other way around. Such a frontier analysis, however, requires scores for animal welfare and environmental impact that differ between farms. Animal welfare scores that differ between farms within the same housing systems, however, are not readily available at farm level.

In past decades, various protocols have been developed to assess welfare on livestock farms, such as the Animal Needs Index (Bartussek et al. 2000) or the Bristol Welfare Assurance Program (Leeb et al. 2004). These protocols use mainly resource and management-based indicators, which measure the state of the environment (e.g. the housing system) rather than the animal. These protocols, therefore, have limited potential to discriminate welfare between farms within the same environment, e.g. the same housing systems. The use of animal-based indicators, however, is gaining increased preference over resource- and management-based indicators in schemes to assess farm animal welfare. Animal-based indicators measure the state of animals rather than their environment and, therefore, are assumed to possess higher validity than resource- and management-based indicators because they are more closely linked to the actual welfare state of animals (Webster et al. 2004; Blokhuis et al. 2010). Animal-based indicators, therefore, have potential to discriminate welfare between farms within the same housing system. Recently, the Welfare Quality (WQ) protocol was developed to assess welfare at farm level for cattle, pigs, and poultry (Welfare Quality 2009). Compared with other protocols, a larger proportion of welfare measures in the WQ protocol are animal-based. This protocol is time consuming, however, it takes about one day per herd (Welfare Quality 2009). The assessment time and associated costs of such animal-based protocols may hamper quantification of welfare for a large number of farms and may hamper a practical implementation of animal-based protocols in welfare audit programs. Marion de Vries, therefore, is currently exploring prediction of animal-based welfare scores using routine herd data (that are available in national databases, such (re)production data), and resource and management data, in cooperation with the Animal Health Service. For this exploration, she was the first to quantify animal-based indicators of the Welfare Quality protocol for a large number of dairy farms.

Figure 5. Frontier of best practices in relation to life cycle assessment (LCA) and animal welfare scores.

Synergies and trade-offs with livelihoods

Keeping livestock is not sustainable if it does not contribute to livelihoods of people, or if it is not a means of supporting one's existence, such as a stable income, employment and food security. We ask ourselves questions, therefore, such as *"can we combine good environmental or animal welfare performance with good farm profitability?"* or "*which intensification strategies contribute to livelihood of smallholders, while maintaining the environment"*?

Results from PhD work of Mark Dolman, working at the Agricultural Economics Research Institute (LEI), for example, show that variation in economic and environmental performance is high among farms for fattening pigs. Some of these farms, however, were able to combine a good economic and environmental performance. In addition, antibiotic use tended to be lower on these best performing farms. While comparing farm characteristics, we observed that herd size was larger for the best performing farms than for the rest of the farms. On average, the best performing farms had more fattening pigs, used more labor, and delivered more pork (in terms of slaughter weight) than the other farms. Feed intake per 100 kg slaughter weight also was lower for the best performing farms than for other farms. Furthermore, the best performing farms used a greater share of by-products in pig diets compared with the other farms. From this study one could conclude that to improve the economic and environmental performance of farms for fattening pigs, we should increase farm size (Dolman et al. 2012).

We hypothesize, however, that in our sample the better entrepreneurs managed the larger farms. It would be interesting to explore this hypothesis further, but the Farm Accountancy Data Network (FADN) of LEI does not yet include data on a farmer's mind-set or management characteristics. Good farm management, or if you prefer, precision management, in my opinion, has great potential to improve the integral sustainability performance of farms.

Exploring relations between the impact on the environment and the impact on the livelihood of people is relevant not only in the developed world, but also in developing countries. In developing countries especially, livestock play a major role in the livelihoods of millions of people (Herrero et al. 2010). Over two-thirds of the people living in these countries obtain a significant portion of their income from livestock-related activities (Tarawali et al. 2011). In addition, mixed crop-livestock systems produce the majority of the cereal and livestock domestic products for households, e.g. about 65% of the beef, 75% of the milk, and 55% of the lamb. The majority of these mixed-crop livestock systems are small-scale systems, also referred to as smallholder systems (Herrero et al. 2009; 2010). Livestock in these smallholder systems often fulfill multiple functions: fertilizer, traction, income, food insurance and financing. Research and development programs have explored the potential of rural smallholders to intensify animal productivity to contribute to food needs and to reduce poverty.

Intermezzo – Example of a development program of smallholders in the past
In the 1960s and 1970s livestock development programs generally included exotic breeds, such as Friesian cows; technology, such as artificial insemination, milk recording, progeny testing; and infrastructure, such as slaughterhouses, feed mills and dairy factories. In other words, they exported breeds, technologies and infrastructure, from the developed world to the developing world. These breeding programs, however, did not fit into local, small-scale farming conditions, where animals have multiple functions, high quality feed is unavailable, and additional infrastructure is missing. All international platforms nowadays agree that it is a myth to think that "exporting" animals, technologies and infrastructure from industrialized countries will contribute to livestock improvement in developing countries.

Udo et al. (2011) concluded that innovations in smallholder systems were adopted only if they fit into household priorities, and were not limited by environmental and socio-economic constraints. Strategies to increase animal productivity not only can be limited by availability and access to resources, absence of infrastructure, unstable prices, and variability in climate, but they also can interfere with the multiple functions of livestock in smallholder systems, which may add up to about 40% of total farm revenues.

Compared to the situation in the sixties and seventies, the situation of smallholders has become more complex. Smallholder systems are currently under severe pressure for several reasons. First, large industrial systems, especially pig and poultry production, have developed in response to the rapidly growing demand for livestock products. This development threatens the livelihood of smallholders because of increased competition for markets and resources. Second, exporting “inferior animal products”, such as chicken wings or backs, to West-Africa (e.g. Ghana) negatively affected commercial poultry keeping in these countries (Dieye et al. 2007). Third, animal production levels in smallholder systems are still low. These low production levels, it is claimed, contribute to, for example, relatively high amounts of greenhouse gas emission or land use per kg animal-source food produced. This claim, however, is only partly true. Correcting for the multiple functions of animals, in these smallholders systems, shows that environmental impact results partly from the fact that a good functioning banking system, for example, is missing in these countries.

Given this complexity, one might wonder, if we should continue to focus on intensification strategies for smallholders. Why not focus on the development of sustainable industrial systems in developing countries to meet the growing demand for animal-source food. In Asia, for example, where the growth of the livestock sector has been substantial, large industrial systems account for about 80% of the increase in livestock products since 1990 (FAO 2005). We need, of course, to assess the impacts of large industrial systems in development countries on the environment, animal welfare and local livelihoods, and to identify potential options for improvement. Similar to our systems, a chain approach is highly important to evaluate the sustainability of these large industrial systems. In rural areas, however, farmers do not have many livelihood alternatives, and smallholder production still is important for alleviating poverty. This is one important reason why policy makers, development workers, and researchers remain committed to exploring intensification strategies that enable smallholders to engage in market-oriented food production while maintaining their livelihood and the environment.

Udo et al. (2011) showed that smallholders do have different possibilities to engage in market-oriented activities, depending on animal species and on household resources. Because of the ability of ruminants to exploit low-quality roughage, smallholder dairying in Kenya highlands, for example, has proven successful in meeting the increasing demands for milk, and thereby improving rural livelihoods. Smallholder dairying in Kenya is often competitive with large industrial dairy farms, because it uses family labor and has low investment requirements.

Our research also showed the importance of chain analysis to guarantee adoption of innovations. Let’s take the example of smallholders keeping poultry. When these smallholders participated in development programs aimed at a change to commercial poultry keeping, but still on a small-scale (100-500 birds), they had to invest in a complete package including housing equipment, day-old chick, purchase of feed, and medicines. To be economically viable, smallholders need to sell their products (eggs, meat) for a reasonable price on the commercial market. Smallholders, therefore, have to become more market-oriented, they have to compete with other smallholders and large industrial systems, and they have to depend less on the other functions of their chickens. Ignoring these post-farm aspects in development programs hinders sustainable adoption of intensification strategies.

Simon Oosting recently developed a framework, referred to as LIVCAF (Livestock Value Chain Analytical Framework) that structures the complexity of value chains in developing countries (Table 2). This framework distinguishes four major value chains. The first chain is characterized by rural production and consumption, and is dominated by smallholder mixed-crop livestock systems. Livestock in these systems have multiple functions: they consume waste, deliver manure or draught power, or serve as capital asset. Labor is the major constraint. The second chain contains rural systems that have specialized to fulfill the increasing demand for animal-source food on urban markets. Major constraints are land and institutional issues, such as chain cooperation, infrastructure and logistics. The third chain contains peri-urban farms that, because of high costs for land, are characterized by high external inputs of feed and water, and high animal densities per ha. Major development constraints, therefore, are feed and water supply, and waste disposal. Finally, urban consumers have access to animal-source food from global markets, produced in specialized systems across the world.

Table 2. Livestock value chain analytical framework (LIVCAF).

Producer-consumer	Dominant system	External feed	Major constraint
Rural – rural	Mixed crop-livestock	Low	Labor, role of livestock
Rural – urban	(Semi)-specialized	Medium	Land, institutional
Peri(urban) – urban	Intensive (no animals/ha)	High	Feed & water supply, waste disposal
External – urban	Specialized	-	Dependency global market

This framework shows that different livestock systems are associated with different value chains, which differ in objectives of animal keeping, role of crop production, level of feed input, and constraints for development. An intensification strategy might require a system jump, i.e. a change from one to the other chain. A smallholder keeping poultry might intensify egg production relatively easily as long as the eggs can be absorbed by the rural market. When he wants to further specialize and produce for the urban market, however, he needs to get sufficient scale for transport, processing and meeting requirements for urban markets. Competition from peri-urban and import chains, moreover, may be a constraint to overcome. This system jump will not only affect potential production of animal-source food but also related environmental impacts.

This framework will be the basis to explore options and constraints for innovations to fulfill the growing demand for animal-source food while maintaining the environment and the livelihood of people. To identify potential innovations, we invested in a PhD project, for example, that is directed at the analysis of the gap in yield between "the theoretically achievable production and actual production" in diverse value chains.

In summary

I started my lecture by sharing with you part of the song *"Het Dorp"* from *Wim Sonneveld*. I wondered if livestock production was more sustainable in former times than today. In my intermezzos, I illustrated that livestock production in former times also affected the environment; that the occurrence of major infectious diseases in animals in Europe reduced; that some housing systems resulting in impaired welfare are being abandoned; and that innovations can be adapted by farmers only if they fit their farming conditions. I do believe, however, that the structure of the animal production sector has changed dramatically, and that today it stands at a critical crossroad.

First, the impact of animal production on the environment in the past was mainly local. The complexity of animal-source food chains, however, has increased, because of industrialization, specialization and globalization. Pork production in the Netherlands, for example, can result in soil degradation or biodiversity loss in South-America, whereas fish consumption in Europe can affect livelihoods of smallholders in East and South-East Asia. Nowadays, different stages along the food chain are disconnected and occur in different areas in the world. Production and consumption of animal-source food, therefore, no longer has only local impacts.

Second, throughout most of human history the increase in demand for animal-source food has been relatively low. In my opinion, the impact of livestock production on the environment and society is currently more severe and more visible than in the past, because the volume and density of production have increased, despite gains in efficiency.

Third, we are now more aware of the fact that different goals of sustainability can be conflicting – such as improving welfare of animals and reducing the environmental impact. Sustainable production of animal-source food, therefore, implies making difficult choices among conflicting goals. This process of decision-making not only requires public dialogues about what kind of food and agriculture we want, but also implies that there is no unique, simple solution to sustainability because agro-ecological and socio-economic circumstances differ across regions.

In my opinion, moving towards sustainable production of animal-source food, therefore, requires three elements: stabilization of the world population, modest consumption of animal-source food, and decision-making based on science. Stabilization of the world population is required because a finite world can only support a finite population (Hardin 1968). Modest consumption of animal-source food (i.e. a reduction of consumption in affluent countries, and an increase of consumption in countries where dietary diversity is limited and malnutrition levels are high) is required to temper the environmental impact of future demands. Decision-making based on science is required to enhance a transparent societal and political debate about future options and limitations of sustainable animal production systems.

Our research aims to contribute to decision-making based on science. We want to analyze how changes in livestock systems connect to changes along the entire chain, in environment impact, in welfare of animals and in the livelihood of people. *Innovation* in animal production requires not only an *integration* of different aspects of sustainability, but also an *integration* of different stages along the animal-source food chain. **Innovation born of integration** includes a re-defined focus on efficiency from a chain perspective, while accounting for competition between animals and humans for resources; an integrated design of systems; precision-management along the food chain, and improved socio-economic circumstances of smallholders.

A re-defined focus on efficiency implies, for example, feeding pigs solely ingredients that are not suitable for humans; breeding beef cattle that use grass from marginal lands efficiently or using food-feed crops, preferably legumes, in smallholder systems.

An integrated system design combines, for example, production of pork and tomatoes. In such a system, pigs are housed indoors, in animal-friendly stalls, on a farrow-to-finish principle. Excreta from pigs are segregated immediately into a liquid and solid fraction. The liquid fraction is used to water tomatoes, whereas the solid fraction is used to generate electricity, in combination with “slaughter waste” and fibre material from the greenhouse. The “surplus heat” from the bio-gas plant is used to heat the greenhouse. The digestate can be used to fertilize tomato cultivation. Pigs consume co-products from, for example, the food industry that are not suitable for humans (Adapted from Nee Rentz-Petersen; Abbott 2010).

Precision management along the chain implies development of knowledge, tools and sensors to use resources efficiently. Did you know that about 50% of the fruit and vegetables produced, and about 20% of the meat produced is lost somewhere along the food chain? In developing countries food is lost mostly during the production-to-processing stages, whereas in industrialized countries, about 50% of this loss occurs at the consumer stage (FAO 2011). We could feed fruit and vegetables to twice as many people and feed meat to more people if we did not have these losses.

Improved socio-economic circumstances of smallholders require policies that deliberately consider the opportunities and threats faced by smallholders. Only a small part of the smallholders, especially the “better-off farmers”, will benefit from the increased demand for animal-source food. Without policy changes that address the current problems faced by poor smallholders, many of these households are likely to be excluded from the increased market opportunities (Udo et al. 2011). Without alternatives, therefore, opportunities to improve the livelihood of these smallholders remain limited.

Science for impact

Our research not only generates knowledge that enhances decision-making regarding sustainable production of animal-source food, but also contributes to the development of tools that *can be* and *are used* by stakeholders along the food chain to improve the sustainability of their products; or by institutions, like the FAO, to evaluate scenarios for sustainable development. I am actually very proud of the “impact of our science on society”. We contributed to the development of “Feedprint”, a carbon footprint tool that will be used by feeding companies to explore strategies that reduce emission of greenhouse gases along the chain, whose development is coordinated by Wageningen UR Livestock Research. In collaboration with the Animal Health Service, we explored the potential of the current Welfare Quality Protocol to monitor welfare on Dutch dairy cattle farms, a key issue for, for example, CONO or Friesland Campina for their future milk supply. The FAO and Nutreco showed interest in applying our most recent knowledge about “water footprinting”. I do believe, therefore, that our work and research contributes to the growing interest of industry to incorporate social responsibility and environmental sustainability in their activities.

One important initiative I would like to mention is our involvement in The Sustainability Consortium (www.thesustainability.consortium.com), consisting of diverse global participants (e.g. retailers like Walmart, Ahold and Unilever; and NGOs like WWF) working together to develop standards and tools to enhance the ability to understand and address the environmental, social, and economic implications of products, along the entire life cycle.

Integrative science

I fully realize that "Moving towards sustainable production of animal-source food" includes many more aspects than the ones we now focus on in our group. These aspects include, e.g., social embedding, food safety, landscape quality, labor circumstances, or the role of governance. A sound scientific exploration of the impact of innovations on the environment, on animal welfare and on people's livelihood along the chain, however, requires a minimum critical mass per issue, justifying my choice for these issues in the years to come. I look forward to building on and expanding cooperation with other research groups that have complementary knowledge to help design a sustainable future, not only for the Netherlands, but also for the world.

The integrative nature of our research implies that we cooperate with diverse research groups in the field of natural, social and environmental sciences, nationally and internationally. The integrative nature is reflected also in our supervision, not only of our MSc students, but also of our PhD students. PhDs form the backbone of research at universities, and, committed supervision is essential for a successful PhD project. Having two or three research groups involved is demanding, involves inefficiencies (as we have to learn to speak each other's language), and requires additional effort. Wageningen UR is well known for its unique position in integrative science. To maintain this position, however, we need appropriate incentives and institutional settings to reward these additional efforts in integrative research. I am convinced that we can innovate only by integrative solutions to today's problems.

Dankwoord (Words of Gratitude)

Dit laatste, meest persoonlijke deel van mijn rede, spreek ik het liefst uit in het Nederlands. Wie had ooit gedacht dat een meisje, dat niet van lezen hield, op school veel kwebbelde, en buitenspelen en gymnastiek het leukst vond, een beroep zou kiezen waarbij je veel moet lezen, hele dagen stil moet zitten en gelukkig nog wel redelijk wat mag praten. Ik niet. Hoe ouder ik werd, echter, hoe leuker ik studeren, nadenken, brainstormen, college geven, schrijven en motiveren, oftewel de academische omgeving vond. Aan dat proces hebben veel mensen bijgedragen. Het is uiteraard ondoenlijk om iedereen bij naam te noemen, maar een aantal mensen wil ik toch expliciet bedanken.

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De leerstoelgroep Dierlijke productiesystemen (DPS) werd na mijn promotie mijn thuisbasis. Herman van Keulen heeft mijn carrière-switch mogelijk gemaakt, door mij 18 jaar geleden bij DPS als universitair docente aan te nemen. In de beginjaren bij DPS heb ik veel steun gehad van Wiebe Koops. Ik bewaar warme herinneringen aan onze discussies over “definitie van systeemgrenzen” en “emergente eigenschappen”. Eind 1999 werd Akke van de Zijpp hoogleraar DPS. Akke heeft mij gestimuleerd deel te nemen aan het “Talents and Topics” traject binnen WIAS. Het is in die periode geweest dat ik opnieuw ben ga nadenken over mijn toekomst. Ik realiseerde mij dat mijn kinderen snel zelfstandig werden, en dat ik graag wilde gaan bouwen aan een eigen onderzoeksgroep.

Ik wil de komende jaren met hart en ziel bijdragen aan het duurzaam produceren van dierlijk voedsel, en ik geloof heilig dat dit enkel kan door geïntegreerd denken en doen. Iedereen binnen onze leerstoelgroep is daarin, op zijn of haar manier, van groot belang. Henk, jij bent een baken binnen DPS, en ik hoop dat het ons lukt vanaf 2013 zelfstandig te kunnen varen. Eddie en Simon, jullie zijn mede-grondleggers van onze nieuwe koers, ik vind het heel prettig samen te navigeren. Karen, jij vormt de motor van ons onderwijs. Erwin, je draagt niet alleen bij aan ons huidige onderzoek en onderwijs, maar jij hebt, onbewust, een heel belangrijke rol gespeeld in mijn persoonlijke leven. Fokje, Theo en Ymkje, jullie werk maakt dat alles binnen DPS op rolletjes loopt. En dan de jonge honden “oftewel de AIO-groep”. Ik vind het geweldig om jullie te mogen gidsen in jullie wetenschappelijke vorming. Jullie enthousiasme en ambitie geven mij energie, en het gevoel dat mijn werk er toe doet. Jullie zorgen bovendien dat ik bij de tijd blijf: zo kijk ik tegenwoordig samen met Jidde naar “The Bing Bang Theory”, en schrik ik niet, maar groet ik terug als iemand zomaar roept “Yo-Man“.

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Prof. dr *ir*. Imke J.M. de Boer

'Livestock production stands at a critical crossroad. Its environmental impact is more severe and more visible because of population growth, rising incomes, and urbanization. Production with respect for the welfare of animals is an important issue in Europe and, increasingly, across the world. Can we produce animal-source food while respecting the environment, the animal and the different actors in the production chain? In this lecture, I will address the importance of "integration" to reveal new directions for the production and consumption of animal-source food.'

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