ELSEVIER

Livestock Production Science 80 (2003) 79–88

LIVESTOCK PRODUCTION SCIENCE

www.elsevier.com/locate/livprodsci

Genetic improvement of livestock for organic farming systems

D. Boelling,[a,*], A.F. Groen[b], P. Sørensen[a], P. Madsen[a], J. Jensen[a]

[a]Department for Breeding and Genetics, Danish Institute of Agricultural Sciences, Research Centre Foulum, P.O. Box 50, 8830 Tjele, Denmark

[b]Department of Animal Sciences, Wageningen University, P.O.Box 338, 6700 Wageningen, The Netherlands

Abstract

Organic farming which experienced a constant rise over the last two decades is a system based on sustainability and on a concept tending towards functional integrity. Legislation as well as the wish to produce separately from conventional farming raise the question whether organic farming should be conducted completely apart from conventional farming or not. This paper discusses the aspects that affect animal breeding under these circumstances, e.g., maintaining genetic diversity by using local breeds and possible G × E interactions which might occur when breeds adapted to conventional farming systems are used in organic farming. Ways of modelling G × E are presented, moreover examples of G × E in dairy cattle, swine, and poultry are given. Trends in selection index theory—designing multi-trait breeding goals including functional traits on one hand, and developing methods for using customised selection indices on the other hand—support breeding work for organic farming systems. It is concluded that before the technical issues can be addressed, all parties involved, farmers, consumers as well as legislators, have to agree on the socio-cultural conditions under which organic farming should be conducted.

Keywords: Organic farming; G × E interaction; Reaction norm curves; Animal breeding

1. Introduction

Organic farming is a concept based on sustainability of agro-ecological systems. Sustainability can be defined as meeting the need of the present without compromising the ability of future generations (WCED, 1987). Thompson and Nardone (1999) described two different methodological approaches to sustainable livestock production: resource sufficiency and functional integrity. Resource sufficiency presupposes that resources necessary for a production process are foreseen to be available in the future, and therefore relies to a large extent on externalising inputs and outputs. Functional integrity stipulates that crucial elements of the system are reproduced over time in the system itself in a way that depends on previous system states. Feedback mechanisms have to prevent critical elements either to disappear or to increase without limits, i.e., the system manages to keep itself in balance. In these feedback mechanisms, diversity and robustness are important and closely linked aspects. While conventional farming tends towards resource sufficiency, also when solving ecological problems, organic

---

*Corresponding author. Tel.: +45-89-99-1263; fax: +45-89-99-1300.

E-mail address: dorothee.boelling@agrsci.dk (D. Boelling,).

0301-6226/02/$ – see front matter © 2002 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0301-6226(02)00323-8

farming tends towards functional integrity of the system. It stresses more the importance of natural processes, the system should be closed and complete in itself, e.g., by restricting inputs on medicines and chemicals (Phillips and Tind Sørensen, 1993), and diversity, robustness, animal welfare, and natural behaviour are highly appreciated.

Organic farming experienced a constant rise over the last two decades. Between 1990 and 2000 alone, the area farmed according to organic rules increased by approximately 32% per year within the EU-15 and corresponded to almost 3% of the total utilised agricultural area in 2000 (Lampkin, 2001).

EU regulations on organic farming (1804/1999) affect mainly three areas: firstly housing, among others in the form of access to free-range areas or grazing; secondly feeding regarding the origin of feed—a minimum of the ingredients should be organically grown-and make-up of ration, e.g., a minimum percentage of roughage in ruminants' diets; and thirdly medical care, e.g., no prophylaxis is allowed, medical therapy is limited, and extended withholding periods are required. In summary, organic farming can be described as a low input system which consequently entails less controlled conditions for farm animals. Therefore, it requires high management quality on behalf of the stockman (Sundrum, 2001; Younie, 2000), and animals well adapted to the respective farming systems (Peters, 1993).

EU regulations recommend that ''a wide biological diversity should be encouraged and the choice of breeds should take account of their capacity to adopt to local conditions'' (EUR-Lex, 1999). However, present organic farmers and those converting their farming system from a conventional to an organic one, usually keep their former livestock. Nauta et al. (2002) discussed several scenarios for organic breeding. These range from developing completely independent programmes to those which are integrated with conventional ones. In the future, the choice for a scenario to be made will depend among others on (1) the wish and need for maintaining genetic diversity in the organic farming system and (2) the required genetic adaptation to the circumstances specific in organic farming (such as feeding and health care; i.e., specific breeding goals and G × E interaction). A genotype well adapted to and performing well in a conventional farming system, might not do so in an organic farming system. No literature is yet available on breeding goal definition specific for organic farming systems or on G × E estimates for conventional versus organic systems.

In this study, socio-cultural aspects of organic farming and biodiversity are discussed to appraise their importance for breeding for organic farming. Moreover, it aims at providing methods to analyse G × E and gives an overview of studies on G × E interaction in cattle, pigs and poultry with regard to organic versus conventional farming systems. The possibilities selection indices offer to organic farming, are discussed.

2. Socio-cultural aspects

Organic farming relies on functional integrity, which has direct effects on the way farm animals including breeding stock, e.g., bulls, are kept, like feeding, housing, and health care. This possibly implies other breeding goals (other traits and different weighting of traits), and furthermore the probability of G × E interaction. Besides, the wish to maintain genetic diversity at a relatively high level is included in the functional integrity approach.

As stipulated by governmental legislation, one aspect of organic farming is to separate—and preferably also to identify—the full production cycle from the conventional one. This facilitates guaranteeing (appraised) product quality and identification of the consumer with the production process. This could require related sectors also to go organic, e.g., organic breeding organisations. Besides it could entail the choice for a different breed that is expected to be more locally adapted—which could additionally be exploited as a marketing tool to enhance the identification process of the consumer, or to obtain other incomes from subsidies on conserving local breeds.

The points mentioned above have an impact on the practical breeding work. Breeding value estimation as well as selection and mating systems are influenced by G × E interactions. Low G × E interactions allow to combine data from several systems; strong G × E interactions imply that data have little information across systems and might require breeding value estimation separately for organic versus conventional systems. The latter scenario is conceptually much more appealing to organic farmers and could go as far as farm-specific breeding based on line or kinship-breeding (Nauta et al., 2002), although it might not lead to any genetic gain. Moreover, the socio-cultural wish to decrease external inputs including semen and to allow for natural behaviour as much as possible support the desire to ban AI, ET and other modern reproduction technologies.

In conclusion, the optimal balance in breeding issues between conventional and organic farmers (or the balance between having a generalised goal and acting together versus having a specific goal and acting apart) is determined by technical aspects like diversity and G × E interactions and socio-economic issues. The technical issues are yet unsolved while from a socio-economic point of view, marketing, and governmental requirements tend to opt for a separation between the two farming systems.

3. Genetic diversity

Today, the genetic variance is decreasing for highly commercial breeds or lines. Especially in dairy cattle for the omnipresent Holstein Friesian breed, the effective population size is estimated to be below 50 animals worldwide (Wickham and Banos, 1998). Pigs and poultry breeding organisations maintain several (synthetic) lines for different commercial purposes, e.g., maternal and paternal lines, laying stock, and broiler lines, besides pure breeds are kept for security reasons in order to preserve hypothetically important alleles. Only in small ruminants, which are not yet intensively farmed and where on-farm conditions vary widely not only nationally but also regionally, a considerable genetic diversity can still be found (Notter, 1999).

Nowadays, successful conventional breeding organisations operate worldwide. They favour highly productive lines which replace original local breeds. But different ways of farming and thus also organic farming, may require a different type of animal, i.e., a genotype which is capable of adapting to the local conditions (Boehncke, 1998). Highly productive breeds need an improved environment (Peters, 1993). Breeds and lines used in conventional systems are not necessarily capable of complying well with conditions in organic farming and the flexibility of the breeds to adapt are questioned. An alternative would be to use local or rare breeds which are hypothesised to be more adapted and robust (Sundrum, 2001).

As mentioned above, using local and rare breeds can also serve as a marketing tool, as consumers equate their favourite product with a specific (local) breed. The decline in genetic variance caused several authors to caution that the genetic and biological diversity should be preserved, also for cultural reasons (Notter, 1999; Hill, 2000). But not only breeds, also a possibly high loss of genes within a breed threatens the diversity and adaptability and should be counteracted (Torp-Donner and Juga, 1997).

The question arises whether the commercial use of local breeds in organic farming systems will guarantee maintaining genetic diversity in the long run. At short notice, the population size will increase, while at long sight, selection and mating within the local breeds will have to balance the genetic trend and inbreeding carefully in order to maintain diversity within the breeds. Generally speaking, it is without doubt that a shift from the current trend to globalise the selection of breeds, e.g., Holstein dairy cattle worldwide, towards more individual and local breeds will favour maintaining genetic diversity across breeds, which also includes providing the robustness and flexibility desired and required in organic systems.

4. Modelling G × E interactions

The (in)ability of animals to express differences in genetic potential for a trait when exposed to different environments, causes G × E interactions (Peters, 1993).

If animals are ranked the same in different environments, no G × E interaction is present. If the ranking is the same, but the phenotypic expressions between two genotypes differ, we talk about a scaling effect of G × E (Falconer and Mackay, 1996, p. 132).

There are three different ways to model G × E interactions statistically.

Given P = phenotype, G = genotype, and E = environment, then the three possibilities are:

$$P = G + E + G \times E \quad (1)$$

$$P = (G + G \times E) + E \quad (2)$$

$$P = G(E) + E \quad (3)$$

Model 1 describes a method where a variance component for a G×E interaction is calculated, e.g., for a herd×sire interaction.

In Model 2, the same trait measured in different environments is treated as a different trait, e.g., milk yield in conventional farming versus milk yield in organic farming. In subsequent bi-variate analyses, the genetic correlation between the two traits can be calculated. A high genetic correlation indicates that the traits are mainly controlled by the same set of genes and can thus be considered as the same trait, while a low genetic correlation denotes that partly different genes are responsible for the expression of the traits (Falconer and Mackay, 1996, p. 322). In that case it is justified to talk about different characteristics. This approach can be further modified by not only defining two environments, but by applying a covariance function so that an unlimited number of traits can be projected over a continuous gradient, as described in Model 3. Graphically, the phenotypes expressed by different genotypes can be illustrated as a function of the environment.

Kolmodin et al. (2002) applied the reaction norm approach when testing for possible G×E interactions in dairy cattle evaluation within the Nordic countries. An increasing co-operation within these countries raises the question whether G×E interactions occur as the environments across these countries are more versatile than within a single country. In this particular study, data of red cattle from Denmark, Finland, Norway and Sweden were pooled and the traits protein production in kg, days open and calving age in months were under investigation.

Fig. 1 shows an example of reaction norms for a random sample of 39 bulls for the trait ‘days open’. Although the genetic variance components of intercept and slope were significantly different from zero (exact numbers not shown here), sires were ranked the same except between extreme environments which is pointed out by the crossing of the lines (Kolmodin et al., 2002).

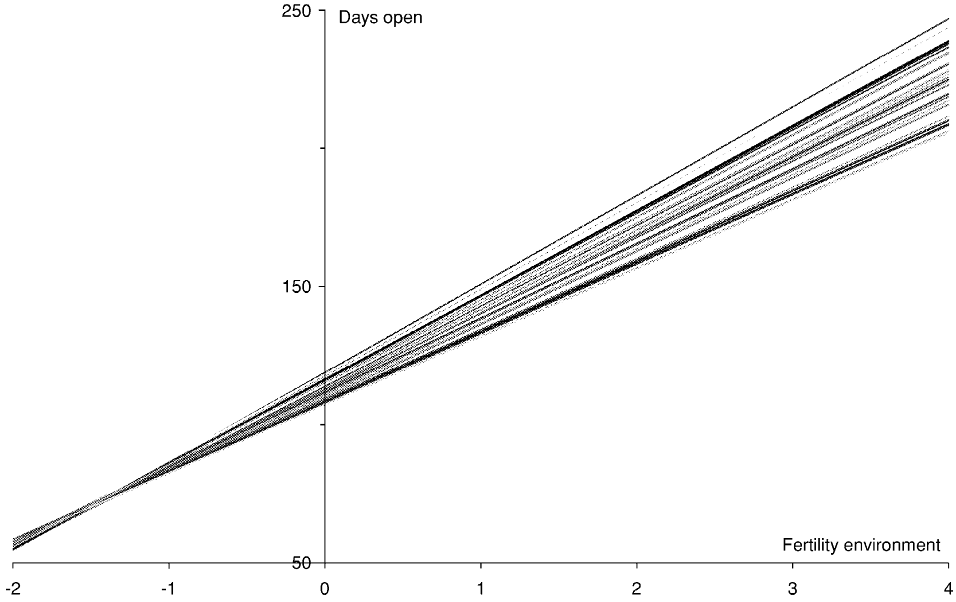

Fig. 1. Reaction norms for days open in different fertility environments, representing a random sample of 39 Nordic red bulls. The *x*-axis shows the deviation from the average environment in SD units of herd-year average.

In another study, Calus et al. (2002) used Dutch dairy cattle protein yield data to compare the three models for their ability to account for G×E interactions. Model 1 detected an interaction variance of 2.5% of the phenotypic variance. When defining E as average protein yield in the herd (estimated herd-year-season effect), Model 2 showed correlations ranging from 0.73 to 0.80. Although the reaction norm model was considered to be theoretically superior, as it calculates breeding values specifically for each environment, it failed to produce EBVs divergent to those of a standard model where the environment defined as herd-year-season subclasses was standardised. The authors concluded that further research like defining different environment parameters, inclusion of differing residual variances, or non-linear reaction norms was required.

The modelling problem is not only to find a continuous descriptor of the environment, but also to find one valid across countries, regions or production systems. In the first instance, Model 2 might be most appropriate for the derivation of G×E interaction (conventional versus organic). In case a significant G×E interaction is observed, Model 3 could help in defining the origin, e.g., clarify the question whether the found interaction is due to a difference in production level, due to an effect of energy content of the roughage, or due to the level of concentrate feeding.

So far, this type of work for modelling data of conventional and organic farming systems is still missing.

5. Examples for G×E interaction

So far, no direct genetic comparisons can be found between conventional and organic farming systems for cattle or swine. In the following sections, examples for cattle, swine and poultry, which resemble best the situation conventional versus organic farming, are given.

5.1. Dairy cattle

Across countries, environments tend to be more versatile than within a single country and G×E interactions become more likely. A good indication for this can be found at Interbull, where genetic correlations for milk traits between the same sires used in several countries are regularly calculated (Interbull, 2002). The production system in Australia and New Zealand is different from that in the USA and Europe, which is reflected in the genetic correlations between countries (Model 2). In general, they average about 0.9 between the USA and/or the European countries, but only 0.8 between Europe or the USA on one side and one of the two South Pacific states on the other side (Interbull, 2002).

Studies looking at different farming systems with different feeding strategies or at different nutritional levels within the same farming system, might offer an insight into the situation on organic farms.

In several investigations, milk yield of Holstein cattle in the US and different South American countries was compared in bi- or multivariate analyses as described in Model 2 (Stanton et al., 1991; Cienfuegos-Rivas et al., 1999; Togashi et al., 1999; Castillo-Juarez et al., 2000; Costa et al., 2000). The different environments within one country were defined by herd-year standard deviations (HYSD), i.e., an HYSD under a certain level described a low herd environment, while an HYSD over a certain threshold was a sign for a high herd environment. Low US conditions and the highest South American conditions were comparable and produced similar yields in the daughters of the same sires, e.g., $r_g = 0.93$ (Cienfuegos-Rivas et al., 1999). When comparing the other classes, genetic correlations varied between 0.61 and 0.72 and either G×E interactions were found (Togashi et al., 1999; Cienfuegos-Rivas et al., 1999), considered possible (Castillo-Juarez et al., 2000) or a scaling effect was detected (Costa et al., 2000).

Pryce et al. (1999) compared two lines, a selection line with high genetic merit and a control line, at different levels of nutrition in one experimental herd. They focussed on health and fertility and could not find any G×E interaction, meaning that different nutritional levels on the same farm did not make the environment different enough in order to cause reranking among the sires.

5.2. Swine

Commercial strains of pigs are bred for intensive production in fully climatised housing systems. In organic systems, animals are free-ranged with a limited application of medicine. So these two aspects—housing and immune status—are of particular interest. A study by Kleinbeck and McGlone (1999) researched the reaction of three commercial pig lines on productivity and immune status in intensive outdoor and indoor housing systems. The results revealed a similar productivity in both systems, but with significant G×E interactions. There were differences in immune measures, but further studies are required before conclusions can be drawn. Reed and McGlone (2000) found comparable results, i.e., G×E for some of the tested immune traits in a similar experiment where another two genotypes were used.

A research project where three different breeds or crosses were compared under organic outdoor conditions over a 3-year period finished in the UK in spring 2002. Only preliminary results have been made available so far, but these indicated that the improved modern Camborough sow produced significantly more piglets in a shorter time than the traditional Saddleback or an improved traditional Saddleback×Duroc cross under the given conditions. Differences in number of piglets weaned or total losses were not statistically significant (Kelly et al., 2001).

The Camborough sow is a very popular female line for conventional outdoor production in the UK, as it is well adapted to that farming system (Kelly et al., 2001). Therefore, it can be expected also to be more productive than the other two breeds in conventional farming, which leads to the conclusion that no G×E interaction could be found.

5.3. Poultry

Egg production is a highly commercialised business nowadays with breeding stock being supplied by very few trans-national companies. Laying hens as small animals with little space requirements, a short generation interval, and high number of offspring facilitate quick success of selection experiments and make it easily feasible to adjust the animal to the environment. One major shift took place when the highly mechanised cage system with minimal space supply was introduced and laying stock bred to fit the new environment, i.e., produce high numbers of eggs in cages.

The shift from floor systems to cages took place in the 1970s; in Denmark only in 1980 due to legislation. Lines already adapted to the new cage system and the Danish Skalborg used in the until-then prevalent floor system were tested in both environments (Table 1).

In the floor system, the Danish Skalborg is equal to the international hybrids. When tested in cages, the international breeds could express their full capacity for laying which is 8% higher than on floor, whereas the Skalborg produces at the same rate in both environments. Moreover, it was observed that the Skalborg had a mortality five times higher in cages than in the floor system, while the international breeds showed a mortality which was 1.5 times higher in the floor than in the cage system. Although a statistical significance for G×E interaction could not be found, it is obvious that the Skalborg breed was genetically adapted to the floor system, while the international hybrids were adjusted to the cage system (Sørensen, 2001).

Lately, a small part of the egg business, i.e., organic egg production, has shifted back to floor systems, and so far, large commercial companies have paid little attention to the requirements of these systems.

In an experiment in a free-range system under semi-scavenging conditions in Bangladesh, which resembles the conditions in organic farming, a locally adapted breed, Sonali, was compared with highly bred Lohmann Brown or crossbred hens (Table 2). The Sonali hen was the best under these conditions, while the Lohmann Brown was very poor in this test, but was capable of producing more than 300 eggs in 12 months in a cage system with optimal feeding and medical care. It was estimated that the Sonali would produce around 200 eggs in a cage

Table 1
Comparison of Danish Skalborg hen with international hybrids in a floor system in 1978 and in a cage system in 1982 (Neergaard, 1978, 1982)

Hybrids	Eggs in 365 days per hen day	
	Floor system, 1978	Cage System, 1982
Average of int. hybrids	268	292
Danish Skalborg	267	266

Table 2
Summary of performance of different breed combinations (Rahman et al., 1997)

Trait	Lohmann Brown	White Leghorn× Lohmann Brown	Sonali
Egg/hen actual	86	99	119
Eggs/hen per 12 months	140	139	156
Mortality (%)	22.1	22.9	16.0
Suppl. feed (kcal)	146	135	130

system (Sørensen, 2001), thus considerable G×E interaction was indicated.

Intensively selected lines of egg layers are perfectly adapted to produce many eggs in cages, but many behavioural traits are suppressed due to the very limited space. These traits surface again when the animals are set into a free range system, like feather pecking and subsequent cannibalism with unacceptably high mortality rates. Moreover, eggs mislaid on the floor instead of in nests and infectious or parasitic diseases not found in cage systems, cause problems. Small selection experiments have shown that these behavioural traits have a genetic basis (see Fig. 2) and ought to be incorporated into a breeding goal for lines used in organic farming in order to make production in the farming system economically sound and acceptable from a welfare point of view.

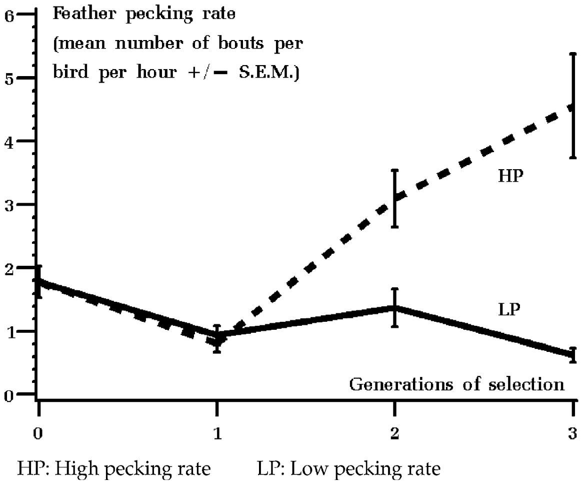

Fig. 2. Effect of three generations of divergent selection for tendency to feather peck (Kjaer et al., 2001).

Summing up, the examples given show that poultry, which relative to other domestic species has been exposed to intense and consistent selection over the longest period in terms of number of generations, has become adapted to a particular farming system. This process is reversible and animals can be adapted to new environments, like those found in organic farming, via selection.

5.4. Summary of G×E interactions

Direct comparisons between different species of farm animals in organic and conventional farming are scarce and therefore data for statistical analyses of G×E interaction hardly available. When looking at studies of performance in different environments, which might be of relevance for organic farming, genetic correlations drop to 0.8 and lower, indicating considerable G×E interaction.

6. Selection indices and new traits

Two general trends can be observed in animal breeding. Firstly, breeding goals which originally used to contain only production traits tend to be developed further to broader breeding goals which include also functional traits. Many examples are known in cattle breeding, e.g., the Danish Total Merit Index represents an early example (Anonymous, 1982).

This index has been improved and extended over the years. Today it includes female fertility, calving ease, mastitis resistance, feet and legs, mammary system, milking speed and temperament apart from milk performance (Anonymous, 2002). Work is also known from other species, e.g., in poultry breeding (Jiang et al., 1998). As a consequence, breeding values are estimated not only on production, but also on a broad range of these functional traits for (potential) breeding animals.

This offers opportunities for a second general trend which is still less pronounced than the first, but nevertheless in the uprising: customised selection indices. Bourdon (1998) developed a vision for beef breeders in the US; in Australia, a PC programme was made commercially available for dairy farmers in 1996 (Bowman et al., 1996). This programme allows farmers to select breeding bulls which suit their farm-specific requirements best. In order to further support this second trend, breeding organisations will have to provide more information on their bulls, e.g., denote whether an animal or its ancestors were born from ET or not, and bulls with specific characteristics will have to be on offer. Finally, programmes will have to be developed which give advice on sire selection, including mating and inbreeding, and on derivation of farm-specific breeding goals like economic values. These customised selection indices are in fact rebalancing the issue of doing things either together or apart. While breeding organisations make generalised decisions on selection in the dam–sire and sire–sire paths when testing young bulls, customised selection indices provide tools to exploit the obtained variance among tested, proven bulls.

Organic farmers benefit heavily from both trends, as EBVs on functional traits which particularly fit their goal, are calculated and as they receive more support for a farm-specific choice of genetic material. The question remains whether EBVs based on data from conventional farming also fit into an organic context. In Austria and Switzerland, work has begun on the development of so-called 'Ecological Indices' in cattle breeding which do not only include production traits, but also fitness or functional traits (Baumung et al., 2001; Bapst, 2001). So far, available data are combined and connected in a new way and bulls receive additionally an ecological breeding value. Whether G×E interactions cause the data collected in conventional farming systems to distort the ecological breeding values, remains to be seen. Studies focusing on modelling organic farming systems and deriving economic values will have to be conducted in order to support customized breeding for organic farming.

7. Discussion

The aim of this study was to highlight aspects influencing (decisions in) animal breeding in organic farming. Besides technical issues like G×E interaction and selection indices, socio-cultural aspects which are based on subjective perception are discussed.

Current opportunities for breeding to support sustainable developments in conventional and organic farming require a multi-disciplinary approach, involving also disciplines like bioethics and animal welfare, and welcoming a philosophical debate (Olesen et al., 2000).

From the technical point of view, several questions have to be addressed like customised sire selection, breeding strategies including the (non)use of AI and other reproduction technologies, and the way how breeding values are estimated appropriately accounting for G×E interaction. This might include further development of analysis tools like non-linear optimisation techniques and reaction norm models and can be done by the respective scientists and experts. The starting point is the question what organic farmers, the citizens, consumers and ultimately the legislator on national and EU level wish to do—this is certainly a subjective matter, but nevertheless a prerequisite in order to solve the technical aspects in the appropriate socio-cultural setting.

The balance has to be found whether organic farming should be generalised and carried out together with conventional farming, or whether it should be conducted apart. When generalising, things done together provide a good basis for rapid progress as a single goal means a high selection intensity. However, generalising technology development includes a common (political) view on how the future farming systems should look like. This common view used to be the 'modern' farm—modernisation of agriculture. Nowadays, the (political) view changes towards a broader range of multi-functional farming systems, including modern farms that are essential for food security at high food safety standards, including farms that have a function in recreation and nature development, and including organic farming systems. Hypothesising that specific farming systems need specific goals, animal breeders need to find a way of renewed balancing 'direction' (what is aimed for in general and specifically for farming systems) and 'speed' (generation interval and selection intensity as defined by selection and mating strategy).

References

Anonymous, 1982. Landskontoret for Kvæg, Statens Husdyrbrugsforsøg—Afd. for forsøg med kvæg og får, Landbohøjskolen—Husdyrbrugsinstituttet. S-index for tyre. Rapport afgivet November 1982.

Anonymous, 2002. The Danish Advisory Centre. Principles of Danish Cattle Breeding. Danish Milk and Livestock Federation. 5th edition, 50 pp. http://www.lr.dk/kvaeg/diverse/principles.pdf

Bapst, B., 2001. Swiss experiences on practical cattle breeding strategies for organic dairy herds. In: The 4th NAHWOA Workshop, Wageningen, 24–27 March.

Baumung, R., Sölkner, J., Gierzinger, E., William, A., 2001. Ecological total merit index for an Austrian dual purpose cattle breed. In: The 4th NAHWOA Workshop, Wageningen, 24–27 March.

Boehncke, E., 1998. Wende in der Nutztierzucht–Ökologische Gründe. Tierärztl. Umschau 53, 63–67.

Bourdon, R.M., 1998. Shortcomings of current genetic evaluation systems. J. Anim. Sci. 76, 2308–2323.

Bowman, P.J., Visscher, P.M., Goddard, M.E., 1996. Customized selection indices for dairy bulls in Australia. Anim. Sci. 62, 393–403.

Calus, M.P.L., Groen, A.F., de Jong, G., 2002. Genotype by environment interaction in Dutch dairy cattle studied by use of reaction norm curves compared to other alternative models. J. Dairy Sci. (in press).

Castillo-Juarez, H., Oltenacu, P.A., Blake, R.W., Mcculloch, C.E., Cienfuegos-Rivas, E.G., 2000. Effect of herd environment on the genetic and phenotypic relationships among milk yield, conception rate, and somatic cell score in Holstein cattle. J. Dairy Sci. 83, 807–814.

Cienfuegos-Rivas, E.G., Oltenacu, P.A., Blake, R.W., Schwager, S.J., Castillo-Juarez, H., Ruiz, F.J., 1999. Interaction between milk yield of Holstein cows in Mexico and the United States. J. Dairy Sci. 82, 2218–2223.

Costa, C.N., Blake, R.W., Pollak, E.J., Oltenacu, P.A., Quaas, R.L., Searle, S.R., 2000. Genetic analysis of Holstein cattle populations in Brazil and the United States. J. Dairy Sci. 83, 2963–2974.

EUR-Lex, 1999. Community legislation in force—Document 399R1804 http://europa.eu.int/eur-ex/en/lif/dat/1999/en_399R1804.html

Falconer, D.S., Mackay, T.F.C., 1996. In: Introduction to Quantitative Genetics, 4th Edition. Langman Group, Essex, 464 pp.

Interbull, 2002. Appendix I. Estimated sire standard deviation. http://www-interbull.slu.se/eval.append022.html

Hill, W.G., 2000. Maintenance of quantitative genetic variation in animal breeding programmes. Livest. Prod. Sci. 63, 99–109.

Jiang, X., Groen, A.F., Brascamp, E.W., 1998. Economic values in broiler breeding. Poultry Sci. 77, 934–943.

Kelly, H.R.C., Browning, H.M., Martins, A.P., Pearce, G.P., Stopes, C., Edwards, S.A., 2001. Breeding and feeding pigs for organic production. In: The 4th NAHWOA Workshop, Wageningen, 24–27 March.

Kjaer, J., Sørensen, P., Su, G., 2001. Divergent selection on feather pecking behaviour in laying hens. Appl. Anim. Behav. Sci. 71, 229–239.

Kleinbeck, S.N., McGlone, J.J., 1999. Intensive indoor versus outdoor swine production systems: genotype and supplemental iron effects on blood hemoglobin and selected immune measures in young pigs. J. Anim. Sci. 77, 2384–2390.

Kolmodin, R., Strandberg, E., Madsen, P., Jensen, J., Jorjani, H., 2002. Genotype by environment interaction in Nordic dairy cattle studied using reaction norms. Acta Agric. Scand., Sect. A, Anim. Sci. 52, 11–24.

Lampkin, N., 2001. Certified and policy-supported organic and in-conversion land area in Europe (ha). http://organic.aber.ac.uk/Eur%20land%20area%20July%2001.htm

Nauta, W., Groen, A.F., Veerkamp, R.F., Roep, D., Baars, T., 2002. Animal breeding in organic farming—an inventory of farmers views. In preparation.

Neergaard, J., 1978. Kontrolstationen for høns 1977/78. Report no. 479 from National Institute of Animal Science, Denmark.

Neergaard, J., 1982. Kontrolstationen for høns 1979/82. Report no. 541 from National Institute of Animal Science, Denmark.

Notter, D.R., 1999. The importance of genetic diversity in livestock populations of the future. J. Anim. Sci. 77, 61–69.

Olesen, I., Groen, A.F., Gjerde, B., 2000. Definition of animal breeding goals for sustainable production. J. Anim. Sci. 78, 570–582.

Peters, K.J., 1993. Selection and breeding strategies for sustainable livestock production in developing countries, with particular reference to dairy cattle production. Occ. Publ. No. 16, BSAP, pp. 119–128.

Phillips, C.J.C., Tind Sørensen, J., 1993. Sustainability in cattle production systems. J. Agric. Environ. Ethics 5, 61–73.

Pryce, J.E., Nielsen, B.L., Veerkamp, R.F., Simm, G., 1999. Genotype and feeding system effects and interactions for health and fertility traits in dairy cattle. Livest. Prod. Sci. 57, 193–201.

Rahman, M., Sørensen, P., Jensen H.A., Dolberg, F., 1997. Exotic hens under semi scavenging conditions in Bangladesh. Livest. Res. Rural Dev. 9(3). http://www.cipav.org.co/lrrd/lrrdhome.html

Reed, S.N., McGlone, J.J., 2000. Immune status of PIC Camborough-15 sows, 25% Meishan sows, and their offspring kept indoors and outdoors. J. Anim. Sci. 78, 2561–2567.

Sørensen, P., 2001. Breeding strategies in poultry for genetic adaptation to the organic environment. In: The 4th NAHWOA Workshop, Wageningen, 24–27 March.

Stanton, T.L., Blake, R.W., Quaas, R.L., Van Vleck, L.D., Carabano, M.J., 1991. Genotype by environment interaction for Holstein milk yield in Colombia, Mexico, and Puerto Rico. J. Dairy Sci. 74, 1700–1714.

Sundrum, A., 2001. Organic livestock farming. A critical review. Livest. Prod. Sci. 67, 207–215.

Thompson, P.B., Nardone, A., 1999. Sustainable livestock production: methodological and ethical challenges. Livest. Prod. Sci. 61, 111–119.

Togashi, K., Yoshizawa, T., Moribe, K., Lin, C.Y., Okamura, Y., Sasaki, O., Yamamoto, Y., 1999. Correlation of international sire evaluations and transmitting abilities based on interaction effects between two countries. J. Dairy Sci. 82, 2030–2038.

Torp-Donner, H., Juga, J., 1997. Sustainability—a challenge to animal production and breeding. Agric. Food Sci. Finland 6, 229–239.

WCED, 1987. Our Common Future. Oxford University Press, Oxford.

Wickham, B.W., Banos, G., 1998. Impact of international evaluations on dairy cattle breeding programmes. In: Proc. 6th WCGALP, Armidale, Australia. Vol. 23, pp. 315–322.

Younie, D., 2000. Integration of livestock into organic farming systems: health and welfare problems. In: 2nd NAHWOA Workshop, Cordoba, Spain, 8–11 January.