

DESIGN OF SUSTAINABLE BREEDING PROGRAMS IN DEVELOPED COUNTRIES

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BACKGROUND

Perhaps the first question to answer here is: in what way does design and sustainability in developed countries differ from that in developing countries? In general, the two problems are the same; getting the maximum possible gain in the breeding goal from the genetic resources available within the technical and environmental constraints that are applied to the breeding program. More specifically, in developing countries breeding goals will often be increasing yields of primary products whilst retaining adaptive fitness, whereas in the developed world it is increasingly about improving health and welfare whilst retaining yields. Schemes in developing and developed countries are both constrained in the genetic resources that can be used either by the need to retain adaptive fitness on the one hand or primary product yields on the other. Again, as a generality, technical capacity will be greater in the developed countries so the challenges will be less about making the fundamental operations of recording, evaluation, selection and dissemination effective, but more about implementing new techniques to address the goals more fully or more precisely. In developing countries environmental constraints will often be direct threats to production from disease or drought, whereas in developed countries such constraints are less direct, but begin to have a real impact through regulations and consumer concerns about pollutants and welfare.

Breeding schemes in developed countries have had considerable success in generating rapid gain in primary yields. This has largely been achieved by focussing on the most productive breed and selecting with high intensity, across herds and populations, primarily for yield. For the most part, environmental conditions have allowed the additional management demands arising from changes in the genotype to be accommodated. Nevertheless there has been a trend for aspects of fitness to decline; in some cases the genetic changes achieved have threatened key elements of some production systems (e.g. annual calving in forage-based dairy systems); there is an increasing interest among producers to in niche markets, raising the possibilities of genotype by market interactions (e.g. organic production); and, at least in the EU, there is an increasingly demanding framework of environmental regulations.

The simplest option is to narrow goals to yield with the hope that management can overcome all the health, welfare and environmental issues. However, this is largely the approach of the past, which has created the current concerns about health, welfare and environment and is therefore not a sustainable option. Thus we need to find ways of clarifying these complex goals and ways of addressing them.

FUTURE DEMANDS AND CHALLENGES

Health, Welfare and Behaviour. Traditional production traits are clearly defined, usually quantitative with substantial heritability, with recording systems tailored towards them. Traits related to health however, are often difficult or expensive to measure, and records on disease incidence are often qualitative (i.e. whether or not the animal had the disease) with environmental clustering. Incorporating disease in breeding goals raises questions on which diseases are important and which are more likely to respond to genetic improvement, both technically in heritability, and operationally in getting the necessary information on which to select. This set of questions is often enough to discourage the setting of meaningful disease goals for some sectors, and furthermore raises the debate over whether generalised immunity or specific immunity should be addressed. Nevertheless the improvement of disease resistance deserves high priority, exemplified by debates within the EU over controls on antibiotic usage in livestock production. These issues are discussed in detail by Bishop *et al.* in this Congress.

It is clear what is meant by animal health. In contrast, for some sectors, the meaning of animal welfare and the opportunity to improve it genetically is unclear, and for some sectors, advances in management may offer the best way forward. For other sectors, there are clearer goals : e.g. in poultry, feather-pecking and cannibalism are problems that have re-appeared with regulations to ban cages. With respect to welfare, therefore, the role of genetic improvement may primarily be to breed for animals that show satisfactory health and yield in production systems accepted by the public.

Fragmentation of Production Environments. Production environments in developed countries are likely to fragment more than in the recent past, through : (i) existing production environments unable to adapt to changes in genotype because of economically important limitations imposed by either nature (e.g. seasonal production) or the market (e.g. organics) ; or, (ii) differing regulatory framework, since it seems unlikely that the framework of environmental regulation will be the same in all developed countries. Within the EU, limits have been placed on emissions of nitrogen oxides and methane from livestock, and other aspects of animal waste disposal are being examined for their health and safety for humans and their environmental impact. Livestock breeding is viewed as being able to provide options to address these issues even though it remains unclear how. Fragmentation leads to potential genotype x environmental (GxE) interactions both between selection and production environments and among production environments. It seems that the fragmentation described above will make such interactions more extreme.

Challenges for Scheme Design. There is no question that the development of two-tier schemes with a nucleus has been very effective in generating gain, aided by the tight management and focus on the goals provided by breeding organisations. It seems certain that such nucleus operations will continue, and that the demands described above will be met within this framework. Therefore the following issues need to be addressed : (i) how to maintain overall response in the face of fragmentation of production environments ; (ii) how to improve or maintain fitness traits more effectively. This will need to be achieved within schemes that will need to take more notice of genetic variation within their populations (see Woolliams, this Congress).

MANAGING GENOTYPE BY ENVIRONMENT INTERACTIONS

The obvious response to genotype x environment interactions is to produce lines for each major environment. It is a feasible solution for pigs and poultry, but unlikely to be so for cattle. However, gain whilst managing the risks [ΔF and $\text{Var}(\Delta G)$] in a breeding scheme, will depend upon the size of the breeding scheme. For all sectors therefore, fragmentation of the breeding populations will demand additional resources if the genetic response (to the new goals) is to be substantial and predictable. Thus alternatives to splitting populations into separate lines are needed.

Reaction Norms. It is clear from the field of evolutionary genetics that the environment of selection has consequences for the genetic change in environmental sensitivity. Selection for performance in good environments increases environmental sensitivity, since the correlated responses (i.e. performance in a poorer environment) are generally smaller than direct responses. Thus the 'reaction norm', which describes the slope of the graph for performance against the quality rank of the environment, increases (Falconer, 1990). This environmental sensitivity can be modelled explicitly using random regression models for the reaction norm, which is an advantage over models including GxE interactions or multi-trait analyses. Significant additive genetic variance has been found for this slope (Kolmodin *et al.*, 2002) and environmental sensitivity can therefore be changed by artificial selection (Kirkpatrick and Bataillon, 1999 ; De Jong and Bijma, 2002). Consequently, it may be possible to explicitly breed for a genotype that shows on average the same phenotype in all environments *as a goal*.

An additional advantage of reaction norms is that the norm for one trait can be examined as a function of the quality of the environment for another trait. Kolmodin *et al.* (2002) suggest that the genetic correlation between production and fertility depends on the environment. In poor production environments the genetic correlation between production and fertility seems to become increasingly unfavourable. This indicates that unfavourable genetic correlations between production and fertility can be counteracted to some extent by providing the cow with a good production environment. However, it also indicates that trade-offs of selection for production may be larger on production herds than effects observed in a breeding nucleus with good environment. Selection for production in a good environment may therefore have larger fitness consequences in common production environments than suggested by the correlated response in the selection environment. The resource allocation model of Van der Waaij (this congress) yielded similar results (see below), indicating that there is a connection between resource allocation and reaction norm models.

DISEASE RESISTANCE AND FITNESS

Since what isn't measured can't be managed, it is clear that addressing the overall level of fitness and the interactions with production environments, will require recording systems to collect more and better, data on health and fitness traits. This will be particularly difficult where recording for breeding is extensive (e.g. ruminants), less so for pigs and poultry where sufficient resources are available within the control of breeding organisations. Evaluation of simple health data suffers from (i) categorical nature of the trait (ii) sporadic incidence (iii) clustering of cases when the disease occurs. Therefore, whilst recording incidence provides an

immediate means of addressing the problem, further benefits may arise from better definition of the phenotypes and refining what is measured and/or evaluated.

Longevity. Longevity is becoming an important breeding goal trait, particularly in dairy cattle where replacement costs are high. When specific health traits are included in the breeding goal and the recording system, the importance of longevity in the breeding goal may be to account for 'general' or 'residual' health that is not accounted for by health traits that are directly selected for. General health may be largely related to metabolic stress, including phenomena such as chronic wasting in dairy cows. Once specific health traits are successfully improved by means of selection, aspects of 'general' health are expected to become more important.

Selection for longevity suffers from : *i*) recordings come (too) late in life ; *ii*) voluntary culling for production ; *iii*) censored records ; *iv*) time-dependent fixed effects (i.e. contemporaries change over time). The Proportional Hazard Model (PHM) deals adequately with *iii* and *iv* (Ducrocq and Soelkner, 1998). Difficulty *i*) is tackled largely by the use of type traits as early predictors. Ideally, this requires extending the PHM to a multi-trait model, but this is complex. Ducrocq (2002) therefore extracted 'pre-adjusted records' for longevity from the PHM, which could subsequently be used in linear multi-trait animal model evaluations including the type traits. Another approach is the analysis of survival scores (animal survives month *x* or not) by linear or binary multi-trait models that include the type-traits (Madgwick and Goddard, 1989 ; Veerkamp *et al.*, 2001). With respect to *ii*), in a breeding goal, we want to predict the component of longevity that is genetic and uncorrelated to yield, which requires multi-trait EBVs for longevity and production. On the other hand, it is argued that the correction for yield may serve as a correction for a management effect (culling for yield), arguing for a phenotypic correction. However, in a simulation study, EBV resulting from both types of corrections were virtually equally accurate in predicting the genetic component of functional longevity (Meuwissen *et al.*, 2002).

Reducing environmental impacts. Besides the sensitivity to macro-environmental changes (described above), environmental variability within a macro-environment (σ_E^2) may be selected for, e.g. to select for more uniformity of traits. First results on litter size indicate that σ_E^2 is heritable (San Cristobal-Gaudy *et al.*, 2001), but this has to be confirmed in other livestock breeding populations. If it were feasible, a reduction of σ_E^2 for health and welfare traits at a constant mean level would be beneficial, because it is the proportion of individuals that fall below a critical performance threshold determining the extent of involuntary culling (See Colleau, this Congress).

Metabolic fitness. Negative genetic correlations between traits related to fitness and production traits are widely observed in livestock improvement (Rauw *et al.*, 1998). Though negative correlations are theoretically expected (Hill and Mbagi, 1998), it requires detailed knowledge of the distribution of gene and mutation effects to predict the value and the change of genetic correlations over time. Because such information is lacking, genetic correlations are commonly treated as "given", without relating them to the underlying biology or genetics. Health problems in high productive breeds are often related to metabolic stress. Apart from the need for data recording for the purpose of breeding value estimation, we need to gain a better

understanding of the physiological background of reduced fitness due to metabolic stress. Such an understanding will identify the parameters of interest, in particular for long-term physiological consequences of artificial selection, with the potential of (i) better defining phenotypes for evaluation from traits recorded, and (ii) identifying better traits to record.

Beilharz *et al.* (1993) have argued that selection for increased productivity will lead to a situation where resource availability is limiting, which in turn causes the correlation between fitness and yield to be negative. This idea is intuitively appealing and might be helpful to understand relationships among traits in populations selected for productivity. Resource allocation may be expressed as a quantitative model, where a total amount of resources, R , is allocated to two body functions in amounts S and F (Van Noordwijk and De Jong, 1986). Allocation is determined by a control coefficient C , so that $F = CR$ and $S = (1-C)R$. S may be regarded as the amount of resources allocated to a (production) trait under artificial selection and F as the amount allocated to traits related to fitness, such as maintenance. The covariance of F and S is given by $\sigma_{F,S} = \mu_C(1-\mu_C)\sigma_R^2 - \mu_R^2\sigma_C^2 - \sigma_R^2\sigma_C^2$. A difference with an additive model is that the covariance of F and S depends on trait levels, so that change of trait levels due to selection can lead to a change of the correlation. When ignoring the term $\sigma_R^2\sigma_C^2$, which is small in general, a positive covariance requires that $\sigma_R^2/\sigma_C^2 > \mu_R^2/\mu_C(1-\mu_C)$. In the extreme case when limited resource availability causes σ_R^2 to be zero, there is a negative correlation of -1 between F and S . Restricted feeding will probably not lead to $\sigma_R^2 = 0$, but it is likely to cause a greater reduction in σ_R^2 than in μ_R^2 , which reduces the covariance. For example, if daily feed intake in pigs is normally distributed with a mean of 2kg and a standard deviation of 0.22kg when feeding is *ad libitum* (Eissen, 2000), then restricting intake to 2kg per day reduces the squared mean feed intake by 17% but the variance of feed intake by 64%. Furthermore, keeping the correlation between F and S constant requires that σ_R increases proportionally to μ_R , i.e. a constant coefficient of variation of R .

A simulation study of Van der Waaij (this congress) suggests that the above model causes G×E-interaction to develop over time when populations are selected in environments that differ in resource availability and when there is natural selection for fitness. Simulation results suggest that the population selected in a good environment shows a substantial reduction in fitness when exposed to a poor environment, whereas the increase in productivity of the population selected in a poor environment when exposed to a good environment is limited. Further details on the above model are in De Jong and Van Noordwijk (1986) and Van der Waaij (this congress).

In the above model, C and R are treated as linear (underlying) traits, whereas production and fitness are non-linear functions of the underlying traits. In real life, we do not know which are the linear traits. Comparison of model predictions with long-term results of artificial selection in different environments is required to assess the predictive ability of alternative models. When the aim is to develop a selection tool, one may argue that non-linear models can be linearised and that selection on the underlying components yields the highest gain (Goddard, 1983). However, in the context of understanding long-term consequences of selection, the purpose of resource allocation models is not to develop selection tools but to identify which parameters are important and what the consequences are for breeding goals and recording schemes.

The critical assumption behind the resource allocation model is that the 'resource allocation process' is the main drive for the observed correlations. This assumption may not always be

correct. For instance, selection for production may take resources away from traits that are not related to fitness, in which traits there is no fitness trade-off. Furthermore, in natural populations females often show anoestrus when intake is limited. This could be explained by the resource allocation model, whereas it could also be explained as adaptation to natural selection. The consequences for selection may be quite different: the former calls for higher intake; the latter probably for selection against the genes that block oestrus. Comparison of the genetic correlation between fitness and production under *ad libitum* versus restricted feeding schemes may serve as a test for the resource allocation model.

The above model stresses the importance of the level and variance of feed intake. With non-linear relationships among traits, fitness consequences of selection for productivity may be larger than expected from the genetic parameters of the base population, in particular when selection aims to improve feed conversion ratio (Meuwissen and Goddard, 1997). This observation is particularly important given the growing environmental regulations that stress the efficiency of resource use. Furthermore, analyses of natural populations suggest that there is a biological limit to the turn-over rate of resources, which is due to increased maintenance requirements of the "production machinery". Studies of species that are evolutionarily specialized in a certain activity reveals that there are no species that spend more than 7 times their resting metabolic rate to this activity (Hammond and Diamond, 1997). Feed conversion ratio may therefore have a biological maximum.

GENETIC DIVERSITY

Genetic diversity is the raw material for animal breeding. Genetic diversity in livestock is substantial due to the existence of local breeds in many countries. However, in most livestock species there are a few dominating breeds; many local breeds are endangered so that between breed diversity decreases rapidly. A decline of genetic diversity is most evident in dairy cattle, where a single breed (Holstein-Friesian) with small effective size dominates the globe.

Between breeds. One reason for the decline of between breed diversity is the emphasis on production traits. Because data on production is generally available but data on health, fitness and local adaptation is often lacking, breeds are primarily judged by their productivity whereas fitness advantages of local breeds may go unnoticed. For example, for reasons of productivity Holstein Friesian genes have been introgressed into New Zealand dairy cattle. Later it became clear that Holstein-Friesians have substantially reduced fertility and survival under New Zealand conditions (Harris and Kolver, 2000). To maintain between breed genetic diversity it is important that local breeds are characterised holistically, so that lifetime productivity and profitability can be assessed. Recording of health and fertility traits and increased awareness of genotype by environment interactions for those traits may contribute to the maintenance of between breed genetic diversity.

Within breeds. Maintenance of genetic diversity within breeds requires managing the rate of inbreeding in those breeds. Particularly in livestock species with a few globally dominating breeds, management of ΔF within those breeds is essential to maintain genetic diversity in that species. When the rate of inbreeding is to be restricted, the breeding goal may be formulated as "maximising genetic gain in breeding goal traits at a fixed predefined rate of inbreeding". Woolliams (this Congress) examines this problem in detail, showing that well defined

procedures exist for selection and also for matings (where specific matings can be designated). This paper makes the observation that by using these procedures breeding organisations can make the same ΔG as they do at present whilst reducing the rate of inbreeding generated.

There is a question over what ΔF can be regarded as sustainable. Empirical observation suggests that $\Delta F \sim 1\%$ per generation is sustainable. Schemes can face substantially greater risk for only a very marginal expected increase in ΔG , since the relationship between ΔF and ΔG becomes highly curvilinear. It can be argued that when ΔF exceeds 1%, and the line is projected to continue for several generations, the projected gains are illusory and are artefacts of the models used for predictions.

MOLECULAR MARKERS

Many health traits are difficult to improve by traditional selection methods, because of low heritability, price of recording, sex limited and/or late in life recording, and may involve challenge tests that can kill valuable breeding animals. Although genetic markers may increase genetic gain for production by a couple of percent, it seems most likely that their biggest impact will come from improving these difficult traits (Dekkers and Hospital, 2001). When the trait of interest cannot be recorded on the selection candidate itself, but good data is available on its relatives, then marker-assisted selection is expected to be beneficial. For traits that are either difficult or expensive to record, data quality and quantity may be a limiting factor for QTL-detection. Suggested benefits of MAS for those situations rely heavily on the assumption that QTL can be detected and that once detected it is possible to select for a number of generations on the QTL without using phenotypic data. However, this requires that QTL are accurately mapped, that the estimated QTL-effect does not need to be confirmed and that the QTL-effect remains constant across a number of generations. These assumptions still require empirical proof.

TOOL DEVELOPMENT

The availability of operational tools such as computer programmes is a key factor for the successful implementation of scientific results in applied livestock breeding. In the past, the availability of software has triggered practical implementation of BLUP and REML procedures. Though software for variance component and breeding value estimation is abundant, software to optimise breeding programs is scarce. One reason is the difficulty to develop general-purpose software that can deal with the variety of designs and population structures found in practice. Theory on the consequences of selection for environmental sensitivity is reasonably well developed and is largely based on existing multivariate regression models. Development of tools to predict and manage genetic change of environmental sensitivity can therefore commence in the near future. Because science is commercialising, tools may no longer be available for free; investment of breeding companies in tool development may become required.

CONCLUSIONS

Genetic improvement of production traits in livestock has been very successful, but it is becoming increasingly clear that there have been trade-offs for traits related to fertility, health and welfare. Future breeding goals will therefore need to put more emphasis on those traits. The increasing scale of livestock improvement and production require that animals show

sufficient levels of health across a range of environments, where care and treatment given to individual animals is limited. This requires breeding for robust genotypes. Evolutionary genetic theory shows that the environment of selection directly affects the evolution of environmental sensitivity. In livestock improvement we therefore need to explicitly model the effect of the selection environment on robustness. Furthermore, better recording systems of traits related to fitness may reveal that local breeds are better adapted to certain environments, which may contribute to the maintenance of between breed genetic diversity.

To enhance productivity, health and welfare in a range of environments, the genetic background of environmental sensitivity should be an important research topic the coming years. The development of an overall theoretical framework that connects models for environmental sensitivity with models of resource allocation would give more insight in trade-offs of artificial selection for productivity and is important to achieve sustainable long-term genetic improvement. This may require a closer co-operation between animal breeding, animal nutrition and quantitative physiology.

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