The role of sustainable commercial pig and poultry breeding for food security

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Implications

• The increasing worldwide demand for animal products and the decreasing availability of resources such as land and water require livestock production to increase its productivity and to reduce its environmental impact. Animal breeding must support this.
• Livestock breeding goals should then broaden in a balanced way, focusing on productivity and efficiency, subject to constraints due to feed availability, environmental load, and animal welfare as well as to possible restrictions due to genotype by environment interaction, antagonisms between traits, and selection limits.
• Commercial poultry and pig breeding goals have been evolving in that direction since the 1950s. At the same time, selection technology is becoming more powerful. As a result of both these developments, animal breeding can make an increasing contribution to sustainable food security.

Key words: balanced selection, food security, pig breeding, poultry breeding, sustainable animal breeding

Introduction

Figure 1 shows that the global population is expected to grow to nine billion by 2050, with people in the upcoming economies adding a lot of animal product to their diets, resulting in a demand-driven livestock revolution (Delgado et al., 1999; Foresight, 2011).

An argument against this, stating that the planet’s carrying capacity does not permit it and opting for policies toward eating less animal product (Garnett, 2010), raises an ethical dilemma: to what extent is it justifiable to deny people in developing economies what they clearly want and finally also get access to? Another (non-exclusive) option is to look for technological solutions (e.g., by increasing livestock productivity).

Animal feed production is increasingly competing for resources (land, water, and fertilizer) with human food and fuel production, urbanization, and nature. Combined with climate change (making production more volatile and harvests more insecure), this will increase feed prices and lead to a demand for livestock that can sustain productivity on diets with decreased nutrient density than before, which calls for improvement of animal resource efficiency.

The UN (2012) projects that by 2050, two-thirds of the global population will live in cities and the rural population will be 8% smaller than in 2010. Because “cities seldom contribute to the production of their food … generally, they simply consume it” (Ghirotti, 1999), fewer rural people will then be producing more food for many more urban people. This again means that productivity will have to increase. The logistics of that urban food chain will likely favor intensive production systems (sustainable intensification: Foresight, 2011) close to cities, which in turn raises demands with regard to their environmental impact, which calls for improvement of animal environmental efficiency.

Lukefahr and Preston (1999) state that intensive animal production systems cannot be regarded as a realistic means of providing food security to the rural poor. Providing food security to the (very large) urban world population is quite another issue. We believe that technologically developed animal production, and the associated breeding sector, have a very important role to play here.

In this article, we consider how the above issues can be improved by poultry and pig through selective breeding: changing animal populations over time and the development of (cross)breeds to express genetic potential in commercial environments. This does not involve transgenics or other GMO technologies (no selection there) nor technologies such as cloning (that is reproduction).

Pig and poultry are major (increasingly so) animal protein sources (e.g., >70% of meat globally; OECD-FAO, 2011). Since the 1950s, animal breeding has been very successful at increasing livestock productivity potential. Since the 1970s, breeding goals have increasingly broadened from a narrow focus on productivity to include a range of other interests: as described in the next section, balanced breeding does simultaneously improve productivity, efficiency, environmental impact, animal health and welfare, food quality and safety, and genetic diversity.

Breeding Goals

A breeding goal defines the desired change in an animal population in terms of the traits of any kind of interest and their relative importance. Commercial breeding goals have to be adapted on a regular basis: the relative value of traits changes over time when there are changes in production conditions, market requirements, and societal developments; insight into the biological background of traits improves; and technology development leads to novel options for selection so that improvement of novel traits becomes feasible.
It is useful to consider breeding goals as in optimization theory: maximization of an objective, subject to constraints to the solution (i.e., political requirements imposed from outside), and subject to restrictions on the data (i.e., biological limitations working from the inside). All of these may change over time. Our food security objective is meat and egg production; major external constraints are feed availability, environmental load (e.g., Capper, 2011), and animal welfare. The internal restrictions are due to genotype by environment interaction (G×E), antagonisms between traits, and possible loss of genetic variation; we cover these in the next section.

Animal feed costs form a large proportion of the total cost of production (around 70%), and as argued above, they will increase over time. Due to increasingly stringent environmental policies, pollutant shadow prices (e.g., Price et al., 2007) will do the same. Productive, reproductive, and environmental efficiency will then become ever more important. Productivity and efficiency traits (the core objective for food security) will thus have to form a steady element in breeding goals, not only for food security reasons, but also because of environmental interests.

**Constraint: Feed Availability**

The food–feed–fuel competition makes arable land an increasingly scarce resource. Improvement of livestock feed efficiency alleviates this, as can be illustrated by a broiler chicken example:

The 2010 global consumption of chicken meat was 86.5 million tonnes (faostat.fao.org), equivalent to 123.6 million tonnes body weight. The feed conversion ratio (FCR) converts this into the required amount of feed; our conservative estimate of the global commercial field improvement in FCR is –0.015 kg/kg each year, equivalent to a cumulative annual savings of 0.015 × 123.6 = 1.85 million tonnes of feed. The main chicken meat producing countries realized a 2010 harvest yield of 466 tonnes of wheat per km² (faostat.fao.org), so the above FCR improvement frees up 1.85 million/466 = about 4000 km² of arable land, an area 1.5 times the size of Luxembourg or 3.3 times the size of New York City. This is a cumulative figure, realized every year.

Decreased feed availability will lead to reduced nutrient density. This translates into G×E, which is covered in its own section below.

**Constraint: Environmental Load**

An important element of the mitigation of livestock-created pollution is reduction of overhead through reduction of animal-days per kilogram of product. This calls again for improvement of productivity and production efficiency. Life-cycle analysis of OECD-FAO (2011) for beef, sheep, pork, and poultry meat in the European Union in 2004 calculated greenhouse gas emissions of 22, 20, 7.5, and 5 kg CO₂-eq per kilogram of product, respectively.

Flock and Heil (2001) summarize Commercial Product Evaluation results from laying hens in Germany; due to improvement in liveability, egg mass production, feed conversion ratio, and body weight, the retention of consumed nitrogen into eggs and body protein changed from 0.269 in 1979 to 0.358 in 1999, representing a 14% reduction in nitrogen excretion per animal in those 20 years. Similarly, 35 years of lean growth rate improvement in pigs has reduced nitrogen excretion by 25% per animal and by 31% per kilogram of protein produced (Knap, 2011). In line with this, feed conversion ratio, a simple trait that has been under selection for decades, is very strongly correlated (r > 0.9) to nitrogen excretion in growing pigs (Shirali et al., 2011).

**Constraint: Animal Welfare**

Animal welfare can be defined in various ways. A working definition for practical animal breeding centers around the homeostatic balance of animals between i) its intrinsic potential and requirements and ii) its production environment, which includes nutrition, housing, health, the social environment, and stockmanship (each to support one of the Five Freedoms of the Farm Animal Welfare Council: fawc.org.uk/freedoms.htm). Based on this, breeding goals can be designed to develop appropriate animals for appropriate production systems supported by appropriate management. An important element here is the contrast between the underlying biology (which can be adapted by selection) and the human perception of animal
Developments in Breeding Goals

It follows from the above that feed availability and environmental load form true constraints to livestock production (e.g., more production means more nitrogen excretion), but not to animal breeding: improvement of the traits related to these issues goes largely parallel with improvement of productivity (e.g., greater animal productivity means decreased nitrogen excretion).

Health and livability traits feature in breeding goals both as important animal welfare traits and as important productivity traits; there is no constraint to an increase of productivity here. Many of the adaptability traits will form a novel element in breeding goals.

Commercial poultry and pig breeding goals have broadened widely since the 1970s, typically including 30 to 40 traits now. More traits are to follow because of continuous trait development, increased data recording efforts, and increasingly powerful statistical methods. Figure 2 shows the increasing complexity over time: the relative focus on productivity decreases and objectives such as efficiency (productive and environmental) and animal robustness increase. With the further development of technology such as genomic prediction (which is routine in pig and poultry now: e.g., Forni et al., 2011; Avendaño et al., 2012; Eggen, 2012), it is increasingly feasible to aim for genetic improvement of objectives such as product quality and animal adaptability.

Whether livestock breeding goals are sustainable into the future depends on the ability of breeding organizations to balance the increasingly complex demands for overall sustainability: food security and sector profitability, environmental load, food safety, and health, welfare, and ethical considerations. This balance is complicated and shifting (because of conflicting relations among these objectives) and politically determined. Figure 2 shows that substantial changes have been made and are likely to continue and, as far as an activity’s sustainability relates to the ability to continue its performance, it therefore looks promising.

Restrictions

G×E

Companies that distribute breeding stock globally must account for differences between selection and production environments. Breeding stock must be able to express its genetic potential in a wide range of production environments. The robustness component of genetic potential is particularly relevant when the production sector expands to more marginal areas and the nucleus populations are in biosecure high-input areas. It follows that selection at the nucleus level should be based on records collected in the production environment. On the other hand, nucleus stock can best express its genetic potential for productivity in high-input conditions as illustrated by the quail selection lines in Figure 5 (which is featured mainly in a later section) where the high protein diet allows for much more genetic change. And production animals raised in biosecure conditions can be delivered to the producer in a high health status.

The obvious solutions are combined crossbred and purebred selection (CCPS; Wei and Van der Steen, 1991) or a commercial sibling test (CST; Kapell et al., 2012a). In CCPS, crossbred relatives (most usefully half sibs) of purebred nucleus selection candidates are recorded in commercial conditions so that their performance data can be combined with nucleus data for breeding value estimation at the nucleus level. PIC has been (and is) applying a CCPS since 2004; Knap and Wang (2012) illustrate how it works out for feed efficiency and related traits in pigs, where genetic improvement in feed intake and particularly net feed efficiency (the traits most affected by the environment) benefits most from this approach.

Aviagen has applied a CST since 2000 to improve broiler chicken robustness by selecting on data from contrasting environments. Sibs of selection candidates are grown in non-biosecure commercial conditions, assessing gut health, digestive, and immune function along with livability, growth, and uniformity. The use of CST data for selection has improved productivity in both environments, increased animal adaptability to the wider range of management circumstances they may encounter in the field, and produced more robust populations with higher liveability and uniformity. Kapell et al. (2012a) evaluate selection for body weight
and footpad dermatitis incidence (FPDI) in broiler chickens under CST. Footpad dermatitis incidence shows little G×E but significant re-ranking of its genetic trend across lines and environments, whereas body weight shows substantial G×E between environments. Moreover, these two traits correlate favorably under nucleus conditions and unfavorably in the production environment.

The G×E component of nutrient density through feed availability (see above) can be approached the same way: the main requirement is reliable performance data from the production environment to be used in breeding value estimation.

The G×E can be visualized in interaction plots; an example on the level of the individual animal is in Figure 3, showing there that daughter groups of AI boars differ considerably more from each other in the more favorable production conditions on the right (genetic potential for productivity is best expressed in high-input conditions, as above), so it is much easier to detect (and exploit and value) superior genetics. Breeding companies have, therefore, an active interest in improving the opportunities of their customers to maximize the expression of genetic potential. This takes place through providing detailed manuals and technical guidelines (e.g., animal nutrition and management) and live consultancy to support good stockmanship.

**Antagonisms**

Genetic improvement is not a straightforward process, as most traits are correlated. When genetic correlations are favorable, selection on one trait will also improve the other one; with unfavorable correlations, the opposite happens. This is a common phenomenon for combinations of robustness traits with production or efficiency traits. The obvious solution is to make the breeding goal more sustainable by including both types of traits and to select all into the desirable direction.

Figure 4 shows two examples of this principle. Although the antagonistic correlation is clearly present and remains in place over time, both traits show genetic improvement so that their combination develops perpendicular to the correlation, which is the result of selection for both traits simultaneously. These examples cover two traits each; as mentioned above and illustrated in Figure 2, commercial pig and poultry breeding goals commonly include many more traits, all of which are under selection simultaneously. Given large enough breeding populations, high selection intensities, proper statistical methodology, and proper data-recording infrastructure, this will maintain a desired balance.

**Selection Limits**

Figure 3. Reaction norms for litter size of 2040 AI boars, with daughter records from 144 farms worldwide, 1993–2006. The horizontal axis quantifies the farm-year-season environment in terms of how it influences trait performance (increasingly favorable from left to right), and the vertical axis gives phenotypic performance. Each trendline shows the linear regression for the daughter group of a particular boar. Modified from Knap and Su (2008).

Figure 4. Genetic trends (the black broken lines) in litter size and piglet survival in a pig line, and growth rate and leg strength in a broiler chicken line. Each colored line shown here is the linear regression through the estimated breeding values of the traits for animals born in a particular year (the shape of the data is illustrated by the dotted pink oval on the left, which spans the majority of the 2009 datapoints). The relationship between the traits remains antagonistic (negative) throughout the years, but the combined genetic change is favorable (positive) due to simultaneous selection on both traits; piglet survival increases while litter size is increasing, and leg strength increases while body weight is increasing, both as desired.
Figure 5. Phenotypic trends of body weight (BW) and oil content (OC) in long-term selection lines of quail, mice, corn, and chicken. Modified from Marks (1996), Renne et al. (2003), Dudley and Lambert (2004), and Johansson et al. (2010). Note that the genetic response to selection depends on selection intensity, population size, and heritability of the selection criterion; all these parameters were likely different in the various populations shown here. CP: crude protein content of the diet.

As we have argued repeatedly, long-term genetic improvement of livestock productivity and efficiency will be an important element of providing food security to a large part of the world population, with constraints due to many external forces. The logical question is whether genetic improvement can continue at all over the long term; will genetic variation not simply run out and improvement come to a halt? It is then useful to see what happens when a population is selected for a single trait for a very long time. This is illustrated in Figure 5 for oil content in corn and for body weight in a few animal species: about 100 generations in most cases and 47 generations in the chicken study. The low-oil-content corn line reached a zero level after 85 generations, and the low-body-weight chicken line seems to have come more than halfway to its asymptote (the smallest Galliform bird species, *Excalfactoria adansonii*, weighs about 35 g; 4% of the starting value of these chicken lines) after 47 generations. But none of the “high” lines show any sign of plateauing, so genetic variation has clearly not been exhausted.

Muir et al. (2008) refer to the above corn results when discussing their own findings on allelic diversity in chickens; when chicken breeds were formed, a very long time ago, many of the alleles that were present in the original ancestor population (especially the ones with low frequency) were lost. Each of the eight ornamental “standardized breeds” that were analyzed here (such as Fayoumi and New Hampshire) have lost on average 93% of the original alleles, whereas about one-half of the original alleles are still present in the combined genepool of the 35 industrial lines analyzed here. Industrial breeding has caused less than one-eighth of this diversity reduction: most of it happened centuries ago, mainly as a result of breed formation, which inevitably results in some inbreeding. The chicken lines of Figure 5 (White Plymouth Rock) took no part in the Muir et al. (2008) study, but should be closely related to their Barred Plymouth Rock research line (the White strain was developed from the Barred population only in 1874; see www.plymouth-rock-poultry.co.uk/whiteplymouthrocks.htm), which has lost 85% of the ancestral alleles. In spite of such a loss of diversity, the chicken line in Figure 5 shows no sign of a plateau for its selection trait, similar to the corn lines in Figure 5 that Muir et al. (2008) refer to when stating that their “findings do not preclude future genetic progress,” and that “new mutations may provide needed genetic variability and contribute to a lack of a perceived selection” plateau.

Mutation forms the common explanation for a regular top-up of genetic variation: new alleles are being created all the time, albeit at a very slow rate. Hill (2008) surmized that “mutation is the source of variation which is fuelling the continued responses seen in the production traits and also help to explain why heritabilities are not falling for say milk yield and poultry body weight or egg number. There is therefore no reason to expect responses to cease as variation will not run out.” Another explanation (capacitating epistasis; selection-induced genetic variance) builds on the release of “cryptic” variation previously hidden in gene–gene interactions: new cohorts of previously neutral genes are brought into play as selection triggers sequential changes in the population’s genetic architecture. This would allow for much “multidimensional genetic change under selection, before entering a phase where further progress depends on new mutation” (e.g., Eitan and Soller, 2004). So the two approaches are not exclusive, and more research will no doubt clarify the picture.

Of course, the loss of a considerable number of alleles has possible consequences for the capabilities of the population dealing with novel conditions such as disease. This leads to the insurance argument for animal genetic resource conservation; we have discussed that issue and its ramifications elsewhere (Knap, 2012).

The main asset of any breeding company is genetic variation: future genetic improvement depends on it more than on anything else. Maintenance of genetic variation, between breeding populations (Aviagen, for instance, maintains more than 30 broiler chicken lines including experimental and unselected control lines) and within them, has therefore high priority. The balance between genetic improvement and inbreeding can be kept under control either using ad hoc restriction on the rate of inbreeding or using optimization software to manage genetic contributions and mate allocation within populations. Based on such strategies of genetic resource management, and on the apparent natural elasticity of the system as described above, it looks as if there will be plenty of genetic variation available to exploit for future animal breeding.

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Literature Cited


