Climate change and the characterization, breeding and conservation of animal genetic resources

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Summary

Livestock production both contributes to and is affected by climate change. In addition to the physiological effects of higher temperatures on individual animals, the consequences of climate change are likely to include increased risk that geographically restricted rare breed populations will be badly affected by disturbances. Indirect effects may be felt via ecosystem changes that alter the distribution of animal diseases or affect the supply of feed. Breeding goals may have to be adjusted to account for higher temperatures, lower quality diets and greater disease challenge. Species and breeds that are well adapted to such conditions may become more widely used. Climate change mitigation strategies, in combination with ever increasing demand for food, may also have an impact on breed and species utilization, driving a shift towards monogastrics and breeds that are efficient converters of feed into meat, milk and eggs. This may lead to the neglect of the adaptation potential of local breeds in developing countries.

Given the potential for significant future changes in production conditions and in the objectives of livestock production, it is essential that the option value provided by animal genetic diversity be secured. This requires better characterization of breeds, production environments and associated knowledge; the compilation of more complete breed inventories; improved mechanisms to monitor and respond to threats to genetic diversity; more effective *in situ* and *ex situ* conservation measures; genetic improvement programmes targeting adaptive traits in high-output and performance traits in locally adapted breeds; increased support for developing countries in their management of animal genetic resources; and wider access to genetic resources and associated knowledge.

Key words: climate changes, livestock breeds, adaptation.

1. Introduction

Animal genetic diversity is critical for food security and rural development. It allows farmers to select stocks or develop new breeds in response to changing conditions, including climate change, new or resurgent disease threats, new knowledge of human nutritional requirements, and changing market conditions or changing societal needs – all of which are largely unpredictable. What *is* predictable is increased future human demand for food. The effects will be most acute in developing countries, where the increase in demand is expected to be greatest, and occur at a rate faster than increases in production (FAO, 2003; 2006a), and where climate change is projected to have its greatest impact.

The global livestock sector is characterized by a growing dichotomy between livestock kept by large numbers of smallholders and pastoralists in support of livelihoods and rural food security, and those kept in intensive commercial production systems. FAO's latest global assessment of breed diversity identifies 7040 local breeds (each reported by only one country) and 1051 transboundary breeds (each reported by several countries) (FAO, 2009a). A breed is a cultural rather than a biological or technical entity (Eding, 2008). A breed covers groups of animals having similar characteristics that depend on geographical area and origin. Most European breeds are well defined, distinct and for a large part genetically isolated. In contrast, Asian and African breeds most often correspond to local populations that differ only gradually. About two-thirds of reported breeds are currently found in developing countries. Local breeds are commonly used in grassland-based pastoral and small-scale mixed crop-livestock systems where they deliver a wide range of products and services to the local community, with low to medium use of external inputs. They are usually not well characterized and described, and seldom subject to structured breeding programmes to improve performance. So-called "international transboundary breeds" of the five major livestock species (cattle, sheep, goats, pigs, chickens), many of them high-output commercial breeds, have

spread globally for use in large-scale, often landless, production systems, where they produce single products for the market (either milk, meat or eggs) with high levels of external inputs.

Most flows of genetic material occur among developed countries, most of which are without zoosanitary restrictions, and involve animals suited to high-input production systems (Valle-Zarate *et al.*, 2006; Hiemstra *et al.*, 2007). More than 90% of exports originate from developed countries, and the share of trade in genetic material from developed to developing countries increased from 20% in 1995 to 30% in 2005 (Gollin *et al.*, 2008). In many cases, the improved components of the high-input management systems needed to express the genetic potential of the high-output breeds have been transferred to developing countries. Industrial systems utilizing sophisticated technology and based on internationally sourced feed and animal genetics already produce 55% of pork, 68% of eggs and 74% of poultry meat globally (FAO, 2003; Steinfeld *et al.*, 2006).

For 36% of breeds the risk status is unknown (FAO, 2009a). The loss of within-breed diversity is not known, although within commercial breeds, high selection pressure, particularly when combined with poor breeding programmes, leads to a narrowing genetic base. About 9% of reported breeds are extinct and 20% are currently classified as being at risk. The species involved in production and marketing systems with fast structural change show high proportions of breeds currently at-risk and already extinct. This includes 38% of chicken breeds, 35% of pig, 33% of horse, and 31% of cattle breeds (FAO, 2009a). Economic and market drivers also made up 28.5% of all responses in FAO's questionnaire survey on threats to animal genetic resources across the main species (FAO, 2009c). It can be expected that multifunctional local breeds continue to play a role in the livelihoods of poor people and in marginal areas.

Livestock production contributes to and will be affected by climate change. FAO has promoted discussion of the environmental impact of different livestock production systems. Consideration of

the livestock sector is crucial for adaptation to, and mitigation of, climate change – because the sector is a large producer of greenhouse gases (GHG). Eighteen percent of global GHG emissions are attributed to livestock – via land use and land-use change (directly for grazing or indirectly through production of feed crops), manure management, and enteric fermentation (FAO, 2006a; FAO, 2010).

Climate change will affect the products and services provided by agricultural biodiversity. But this biodiversity has not yet been properly integrated into strategies for adaptation to and mitigation of climate change. Its role in the resilience of food systems still needs to be addressed. The Intergovernmental Panel on Climate Change (IPCC) report on biological diversity (Gitay *et al.*, 2002) and likewise the report of the Convention on Biological Diversity on climate change (CBD, 2009) contain little mention of agricultural biodiversity, and a recent literature review (Campbell *et al.*, 2009) largely ignores livestock diversity. In a survey on threats to livestock diversity (FAO, 2009c), climate change was only mentioned as a minor factor in the context of extensive land-based production systems. The findings show that many stakeholders do not yet perceive climate change as a problem for the management and conservation of livestock biodiversity.

In addition to the IPCC reports describing the predicted impact of climate change on ecosystems and agriculture (Easterling *et al.*, 2007), several papers provide a general overview of the expected impact of climate change on livestock production (Adams *et al.*, 1998, Smit & Skinner, 2002). Other papers model changes in production systems and species composition under climate change (Seo & Mendelsohn, 2007, 2008), poverty impact (Thornton & Herrero, 2008; Jones & Thornton, 2009) or projections of methane (CH_4) emissions from African livestock (Herrero *et al.*, 2008). De La Rocque *et al.* (2008) provide an overview on the impact of climate change on animal diseases.

The big mismatch between the low resolution of available data and the complexity of agricultural

production systems makes it difficult to model the effects of climate change even for organisms with well-known environmental envelopes (Jarvis *et al.*, 2008; Jones & Thornton, 2009). Bio-geographic models exist for the reaction of some well-described crop species to climate change. In the simplest case they project temperature and/or precipitation changes spatially and adjust the area under which a specific crop is able to produce. For some crop and forest species with known migration rates this allows the production of regional or national maps of projected species distribution (Lane & Jarvis, 2007; Zullo, 2008; Seppälä *et al.*, 2009). For livestock, such projections are more complicated: Firstly, several species were domesticated in the same region, implying that they have similar environmental envelopes. Secondly today, many breeds of the major livestock species are globally distributed, implying that the geographic distribution of specific breeds is overlaid by different production systems. In addition, detailed data on most breeds' adaptation traits, including their thermal neutral zones and spatial distribution, are not available (FAO, 2008b). Consequently, breed-level predictions or bio-geographic models of the implications of climate change on livestock diversity are hardly possible with current data. Therefore, instead of trying to predict the survival or movement of specific breeds under climate change scenarios, this paper aims to shed light on the likely sensitivity of breed diversity to climate change and related drivers, the production and ecosystems breeds depend upon, and the goods and services they supply. For the purpose of this paper, a conceptual approach based on a simple overlap of breeds and production systems is used to identify possible implications of climate change for breed diversity (Table 1).

2. Livestock adaptation differences relevant for climate change adaptation

Genetic mechanisms influence fitness and adaptation. Barker (2009) defined adaptedness as the state of being adapted, the ability of breeds to produce and reproduce in a given set of

environments, or the choice of particular breeds for specific environments. Adaptability is then a measure of potential or actual capacity to adapt, for example if one breed is used in different environments. Adaptation traits are usually characterized by low heritability. In relatively stable environments, such traits have probably reached a selection limit; however, they are expected to respond to selection if the environment shifts, resulting in change of fitness profiles and increase in heterozygosity (Hill & Zhang, 2009).

Physiological stress and thermoregulatory control

Heat stress is known to alter the physiology of livestock, reduce male and female reproduction and production, and increase mortality. Livestock's water requirements increase with temperature. Heat stress suppresses appetite and feed intake; thus feeding rations for high-performing animals need to be reformulated to account for the need to increase nutrient density. Body temperatures beyond 45–47 °C are lethal in most species. Heat stress is an important factor in determining specific production environments already today (Zwald *et al*., 2003). Temperature is predicted to increase globally, with reduced precipitation in many regions, particularly in already arid regions.

While substantial differences in thermal tolerance lie between species, there are also differences between breeds of a species. Ruminants generally have a higher degree of thermal tolerance than monogastric species, but species and breed environmental envelopes overlap. The ability to thermoregulate depends on complex interactions among anatomical and physiological factors. Factors such as properties of the skin and hair, sweating and respiration capacity, tissue insulation, the relationship between surface area per unit body weight or relative lung size, endocrinological profiles and metabolic heat production are known to influence heat loads, but the underlying physiological, behavioural or genetic mechanisms are largely unknown (Hall, 2004; McManus *et al.*, 2008). With increasing milk yield in dairy cattle, growth rates and leanness in pigs or poultry,

metabolic heat production has increased and the capacity to tolerate elevated temperatures has declined (Zumbach *et al.*, 2008; Dikmen & Hansen, 2009). In the long term, single-trait selection for yields will therefore result in animals with lower heat tolerance.

Measurement of the effects of heat and other stressors is difficult. The effect of heat stress on milk yield at specific test days is more immediate and easier to measure than on growth (Zumbach et al., 2008). After research on heat resistance of different species in the 1970s and 1980s, there is still today a lack of experimentation and simulation of livestock physiology and adaptation to climate change, which makes it difficult to predict impacts or develop adaptation strategies. In addition to standard physiological measures of heat stress, such as rectal temperature or heart and respiratory rates, measurements of net radiation and convection are required to evaluate the implications of heat stress in extensive grazing systems (Howden & Turnpenny, 1998). Heat tolerance tests will give misleading results unless modifying factors such as age, nutrition, state of health, reproduction and emotion, physical activity, level of production, acclimatization and management are taken into consideration (Bianca, 1961). However, research into behavioural or metabolic breed differences is in its infancy.

A wealth of literature is available on adaptation differences between zebu and taurine cattle (Frisch, 1972; King, 1983; Burns *et al.*, 1997; Prayaga *et al.*, 2006). *Bos indicus* is generally more heat resistant than *Bos taurus* (Burns *et al.*, 1997), with zebu cattle maintaining lower rectal temperatures, lower respiration rates and lower water requirements than taurine breeds (King, 1983). However, research is biased towards few breeds. Many of these studies involved international transboundary cattle breeds, dairy more than beef. There are fewer breed-level studies of local breeds within the taurine or zebu cattle groups, and even fewer in other livestock species. In general, the high-output breeds originating from temperate regions that provide the bulk of market production today are not well adapted to heat stress. Milk production, fertility and

longevity, in Holstein Friesian cattle for example, decline as temperature increases (West, 2003; St-Pierre *et al.*, 2003). Large White sows are less heat tolerant than Creole sows (Gourdine *et al.*, 2006; Renaudeau *et al.*, 2007).

On the other hand, many species and local breeds, particularly those from the Near East and Africa, are already adapted to high temperatures and harsh conditions (FAO, 2006b). The distribution of some domesticated species is completely or mainly restricted to arid lands. Camelids are mostly found in arid areas, with the species differing in their adaptation to altitude and climatic zones. Yaks are adapted to very harsh high-altitude environments in the Asian drylands. More than 70% of breeds of ass, around 50% of sheep and goat breeds, and 30% of cattle and horse breeds reported are adapted to arid areas (FAO, 2006b). Most local breeds are, however, not well characterized and their adaptation includes not only heat tolerance but also to their ability to survive, grow and reproduce in the presence of poor seasonal nutrition as well as parasites and diseases. Breeds adapted to these dry areas will more likely be affected by natural resources degradation linked to climate change rather than temperature or precipitation change *per se*.

Nutritional stress

Breed and species differences in diet selection in sheep and cattle have been observed, linked to different metabolic profiles (Blench, 1999; Jauregui *et al.*, 2008; Fraser *et al.*, 2009a,b). Hayes et al. (2009a) noted that there is more genetic variation in dairy cattle sensitivity to feeding level than to heat stress. Breeds differ with regard to their mobilization of body resources to cope with periodic underfeeding and cease reproduction at different levels of body weight loss. Also rumen physiology, the ability to walk and reach scarce feed resources, to intake water and rehydrate, or to respond with increased night-time grazing to high afternoon temperatures, or even genetic aspects of diet selection play a role (Hall, 2004). The relationships between energy reserves,

endocrinological parameters and breeds' reproduction performance need further attention.

Contrary to other species, feed intake and digestibility in dromedaries did not decline under heat stress (Guerouali & Wardeh, 1998). Among cattle, zebuine breeds generally deal better with low-quality forage than do taurine breeds, while taurine breeds have a better feed conversion ratio (FCR) with high quality feed. Livestock can compensate the expected climate change induced shrub encroachment to a certain extent if the animals are able to select high-quality diets from different plant components or species. However, there is more anecdotal than scientific evidence for breed differences in feeding behaviour and browsing ability. For example, the West African Sokoto Gudali (Blench, 1999) and the South African Nguni (Bester *et al.*, 2002) cattle breeds seem well adapted to browsing. Merino and Dorper sheep, Welsh Mountain and Scottish Blackface sheep (Fraser *et al.*, 2009a, b), and Cashmere and Celtiberic goats (Jauregui *et al.*, 2008) differed in their grazing/browsing behaviour. More research on breed differences in feeding behaviour and adaptation to specific environments is therefore needed.

In addition to diseases affecting the animal itself, a new range of pests and diseases will impinge on crop and forage species, thus affecting the quantity and quality of livestock feeds.

Disease stress

Climate affects vectors, pathogens, hosts and host-pathogen interactions from the level of cellular defence to that of the habitat. Hoberg *et al.* (2008) provide an overview of predicted responses of complex host-pathogen systems to climate change. Climate change may affect the spatial distribution of disease outbreaks, and their timing and intensity. Outbreaks of African horse sickness, peste des petits ruminants, Rift Valley fever, bluetongue virus, facial eczema and anthrax are triggered by specific weather conditions and changes in seasonal rainfall profiles. The predicted

reduction in the availability and quality of water will increase the risk of water-borne diseases for humans and livestock.

Climatic effects on host-vector and host-parasite population dynamics will further the geographic expansion of vector-borne infectious diseases (e.g. Rift Valley fever, bluetongue and tick-borne diseases) to higher elevations and higher latitudes and affect the transmission and course of the diseases (Rogers & Randolph, 2006). However, expansion of the range of a pathogen or vector does not necessarily result in wider disease transmission (De la Rocque *et al.*, 2008). For some diseases, abundance of competent hosts and the effects of risk factors, such as the movement of animals and changes in production systems, habitats and ecosystems, will remain more important than climate change (Rogers & Randolph, 2006; Randolph, 2008, 2009). The possible impact of bluetongue on endemic sheep breeds in the UK is raised by Carson *et al.* (2009).

Rapid spread of pathogens or even small spatial or seasonal changes in disease distribution may expose naïve livestock populations to new diseases. Such newly-exposed host populations lack resistance or acquired immunity; this may result in more serious clinical disease. The expected increased and often novel disease pressure will favour genotypes that are resistant or tolerant to the diseases in question. FAO (2007a) lists breeds, mainly from developing countries, that are reported to be resistant or tolerant to trypanosomiasis, tick burden, tick-borne diseases, internal parasites, dermatophilosis, or foot rot (59 cattle breeds, 33 sheep, 6 goat, 5 horse and 4 buffalo breeds). Again, many of these reports are based on anecdotal evidence rather than scientific studies, and the underlying physiological and genetic mechanisms are not well understood. Various studies have been undertaken to map genes (e.g. Regitano *et al.,* 2008) and study gene expression (e.g. Berthier *et al.,* 2008) in relation to these diseases, but no reports verifying causal mutations have been produced.

3. Climate change adaptation of livestock production systems

The IPCC has defined "Adaptation" as "Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected *climate change* effects". There are many ways in which producers can adapt to climate change. Without judging possible differences in the efficiency of these measures, the paper focuses on the utilization of animal genetic diversity as one option for climate change adaptation. Producers can adapt to climate change by adapting their animals' genetics to the changed environment, or by adapting the production environment while maintaining the animal genetic portfolio. It is assumed that farmers will first use adaptation technologies that can be quickly deployed, and will only change their genetic resources portfolio when it becomes unavoidable. Climate change adaptation can be considered in two ways:

i)   How can animal genetic resources cope with and adapt to climate change while continuing to contribute to food security and rural livelihoods?

ii)   How can the option value of genetic resources be maintained and potential loss of diversity minimized in the event of climate change?

Adaptation of husbandry practices

Frankham (2009) notes that the adaptation of high-output breeds to confined production environments is a recent phenomenon. The direct effects of climate change on housed livestock are expected to be small, as management can compensate for losses in animal fitness by modifying the environment. A variety of technologies can be used to deal with the effects of short-term heat waves, including shading or sprinkling to reduce excessive heat loads (Marcillac-Embertson *et al.*, 2009). Access to these technologies and to capital will determine the ability of producers to protect their herds from the physiological stress of climate change. Intensive livestock production systems

have more potential for adaptation through technological changes and this may make them relatively insensitive to climate change and allow high-output breeds to be retained (Adams *et al.*, 1998). Freitas *et al.* (2006), for example, found that effects of heat stress were smaller in larger herds, which were more likely to afford high-efficiency cooling devices.

The widespread adoption of such technologies will also depend on the availability and prices of energy and water. The question is: How long can the production environment of high-output breeds be maintained in view of expected increases in feed, energy and water prices? In extensive or pastoral systems, where the rate of technology adoption is generally low, or in regions that already today have a limited capacity to adapt (e.g. sub-Saharan Africa), the risk of breed displacement or loss may increase. However, local breeds under traditional management are generally more resilient to environmental changes than are high-output breeds.

Species and breed shifts

Shifts due to agro-ecosystem changes

The use of multi-species and multi-breed herds is one strategy that many traditional livestock farmers use to maintain high diversity in on-farm niches and to buffer against climatic and economic adversities (Hoffmann, 2003; FAO, 2009b). Such traditional diversification practices are useful for adaptation to climate change. Seo & Mendelsohn (2007, 2008) modelled that small farms in developing countries were found more climate change resilient due to their more diverse species portfolios, the ease with which they can shift between species and diversify, and their reliance on goats and sheep. On the contrary, commercial dairy and beef operations were more vulnerable than small farms, because their specialized nature makes it difficult for them to switch to other species.

Several livestock species-level models (Herrero *et al.*, 2008; Seo & Mendelsohn, 2008) that take

into account the direct effects of climate change together with changes in agro-ecological conditions and production systems indicate that farmers will switch from cattle and chickens towards goats and sheep as temperature rises. The models agree that in Africa, livestock in semi-arid rangelands will expand at the expense of humid and temperate/tropical highlands systems, they differ, however, in the relative share of these shifts. Seo & Mendelsohn (2008) predict that ruminant numbers in rangelands will increase as long as there is sufficient precipitation to support vegetation growth. Jones and Thornton (2009) predict that livestock keeping will replace cropping in today's marginal mixed crop-livestock systems as they become ecologically and socially more marginal. In contrast, Herrero *et al.* (2008) model shifts of livestock populations from rangeland-based grazing to mixed systems based on improved feeding of crop by-products. The outcomes of these models imply different breed portfolios, as local breeds are more adapted to pastoral systems.

Species substitution due to climate and vegetation changes has already been observed in the Sahel, where dromedaries replaced cattle, and goats replaced sheep, following the droughts of the 1980s. In countries such as Niger and Mauritania, and in northern Nigeria, camel rearing is now a common activity. Unlike cattle and sheep, which largely feed on herbaceous vegetation, camels browse on shrubs and trees, while goats use both strata. The use of browsing species has several advantages: the browse strata cannot easily be used by other species and tends to offer green forage also during the dry season; and browse is increasing in some environments due to overuse of the herbaceous layer. While species and breed displacement from the arid and semi-arid to the sub-humid zones in West Africa has been observed, extension into the humid zones, where disease pressure is high, is still limited (Gouro *et al.*, 2008; Seo & Mendelsohn, 2008).

Environmental degradation may exacerbate the impact of climate change and raise the costs of climate change adaptation. The recent restriction imposed on grazing in provinces of Western China with the objective of reducing rangeland degradation (Zhang & Hong, 2009) is an example

that may affect local breeds of ruminants.

Shifts due to climate change mitigation measures

Despite contributing only 25% to GHG emissions from the livestock sector (FAO, 2006a), public discussion focuses on enteric fermentation in ruminants. Reducing livestock numbers, increasing individual animal resource use efficiency and optimization of feed rations and feed additives or other technologies may be primarily used to reduce CH_4 excretion in ruminants. In general, CH_4 output increases with the higher dry matter intake linked to high performance, however, the production pathways of different animal products differ in their GHG emissions and this may influence the future emphasis given to different production systems – and the related breeds. For beef cattle, intensive feedlot systems give rise to less CH_4 per unit of meat produced than do extensive grazing systems, because CH_4 decreases as the proportion of concentrate in the diet increases, and because of faster growth rate and shorter time to market. Milk protein can be produced with less CH_4 emission than beef (Williams *et al.*, 2006); CH_4 emission per kg of milk declines as production increases, but with a diminishing rate. In a live-cycle-assessment of global GHG emissions per kg of fat and protein corrected milk, Gerber & Vellinga (2009) found that intensive and mixed farming dairy production had lower emissions than grassland based systems. Also, industrialized countries have lower emissions than developing regions. Improved genetic potential of the cattle, increased feed quality and manure management will reduce emissions from extensive systems. In an intermediate GHG reduction scenario, dairying might become the major focus of cattle production, and beef may become a by-product of dairying. Dual-purpose breeds and crossbreeding may gain importance (Flachowsky & Brade, 2007).

Local ruminant breeds with their relatively lower output and higher GHG emission per kg of single food products are considered unproductive. However, the productivity equation should take account of the multiple products and services provided by livestock in most smallholder and

pastoral production systems (Ayalew *et al.*, 2003). When considering GHG emissions from enteric

fermentation, account should be taken not only of the gross efficiency of converting feed inputs to

human food, but also of differences in species' ability to use forages that cannot otherwise be used

by humans, historical and alternative herbivores (e.g. wild ungulates) and C-sequestration in

grasslands which may partially offset GHG emissions from other components of the production

process. Improved pasture management (e.g. restoring soil organic matter, reducing erosion,

decreasing biomass losses resulting from burning and overgrazing) has positive environmental

effects (soil C-sequestration, biodiversity) and a favourable impact on livestock productivity (Smith

et al., 2007). Gill and Smith (2008) propose using 'human edible return' as another indicator to

assess livestock efficiency. This would favour the return of herbivore livestock species to forage-

based feeding and land-based production systems and result in a different breed portfolio than the

intensification pathway.

Breeding for climate change adaptation and mitigation

Although the direct effects of climate change on the animals are likely to be small as long as

temperature increases do not exceed 3° C (Easterling *et al.*, 2007), projections suggest that further

selection for breeds with effective thermoregulatory control will be needed. This calls for the

inclusion of traits associated with thermal tolerance in breeding indices, and more consideration of

genotype-by-environment interactions (GxE) to identify animals most adapted to specific

conditions.

Breeding for climate change adaptation or mitigation will not be fundamentally different from

existing breeding programmes; however, the problems related to measuring the phenotypes relevant

to adaptation have to be overcome. In the past decade, breeding goals in many commercial

breeding programmes have broadened through changes in selection indices and aim to improve

production, longevity and functional traits simultaneously – for example in dairy cattle, pigs and layer chickens (Wall *et al.*, 2008). As a result, correlations between breeding values with broader indexes that include functional traits are lower than those with production traits only (Mulder *et al.*, 2006).

Correlations between the performance of genotypes in different environments are less than unity because of GxE, differences in trait definitions, and differences in data collection and analysis procedures (Zwald *et al.*, 2003). Such correlations between breeding values are lower in high temperature countries suggesting that heat stress plays an important role in GxE (Zwald *et al.* 2003). Biologically important GxE is assumed if the correlations between the performance of the same genotype in different environments are below 0.8 (Robertson, 1959). A single breeding programme with progeny testing of sires in different environments and applying index selection to simultaneously improve performance in those environments is recommended for genetic correlations between environments higher than 0.6. At lower genetic correlations between environments, environment-specific breeding programs are necessary to breed for special adaptability (Mulder *et al.*, 2006).

Heat tolerance

Finocchiaro et al. (2005) proposed the use of heat-resistant individuals in a sheep breeding program as a main strategy to improve animal welfare and productivity in hot climates. Various physiological and blood parameters differ between local and exotic cattle breeds in Brazil (McManus *et al.*, 2008). Several Latin American cattle breeds with very short, sleek hair coat were observed to maintain lower rectal temperatures, and research in the major "slick hair" gene which is dominant in inheritance and located on Bovine Chromosome 20 is ongoing (Olson *et al.*, 2003; Dikmen *et al.*, 2008). Collier *et al.* (2008) suggest that there is some opportunity to improve heat tolerance through manipulation of genetic mechanisms at cellular level.

Selection for heat tolerance in high-output breeds based on rectal temperature measurements and inclusion of a temperature-humidity index (THI) in genetic evaluation models are promising. Different parameters, such as THI or dry-bulb temperature measurements, are used as indicators for heat stress (Finocchiaro *et al*., 2005; Bohmanova *et al*., 2007; Dikmen & Hansen, 2009). Different THI definitions were found prefable in the US, depending on the extent of natural and artificial evaporative cooling (Freitas *et al*., 2006; Bohmanova *et al*., 2007). The genetic variance due to heat stress was substantial at high THI (Ravagnolo & Misztal, 2002).

However, in the dairy sector it may be difficult to combine the traits desirable for adaptation to high temperature environments with high production potential, because there seem to be different physiological and metabolic processes controlling heat tolerance and milk yield on the one hand, and heat tolerance and reproductive performance on the other (Ravagnolo & Misztal, 2002; Bohmanova *et al.*, 2005, 2007). In beef cattle, the genetic antagonisms between adaptation to high temperature environments with high production potential seem to be more limited than in dairy, and improved characterization of adaptive traits, use of reproductive technologies and molecular markers, and strategic crossbreeding are being incorporated into programmes, for example in the Australian beef Cooperative Research Centre (Prayaga *et al.*, 2006).

Productivity and feed efficiency

Increasing productivity is a condition *sine qua non* for all production systems because of the need to make efficient use of the available inputs and to reduce the livestock sector's environmental footprint. In addition to selection for increased production *per se*, any selection that reduces mortality and increases early maturity, fertility and longevity tends to contribute to reducing GHG emissions per unit of output. Breeding for high performance and improved FCR, and reduced mortality due to better hygienic management, have significantly reduced the amount of feed (and

land needed to produce this feed) per unit of product – more in monogastrics and in dairy cattle than in beef cattle or sheep (Flock & Preisinger, 2002; Capper *et al.*, 2009). Jones *et al.* (2008) investigated the role of genetic improvement in a Life-Cycle-Analysis model in the UK and found that the annual reduction in GHG emission ranged from 0.8% in pigs and dairy cattle to 1.2 and 1.3% in broilers and layers, respectively. The largest contributions in broilers came from improved FCR, and in pigs from improvements to growth rate and fertility. Genetic gain in milk performance has considerably reduced the environmental impact of diary production in the USA (Capper et al., 2009). Future options for selection in ruminants lie in the host components of rumen function, in post-absorption nutrient utilization and in disease resistance. In pigs and poultry, the genetic variation in digestion parameters can be exploited (Warkup, 2007).

In addition to potential for fertility improvements in ruminants – for example decreasing the age of first-calving in zebuine cattle – there is sufficient genetic variability in feed intake, independent of liveweight and daily gain (Flachowsky & Brade, 2007) to permit selection for this trait. Assuming that future dairy systems may become more reliant on pasture than grain feeding, Hayes *et al.* (2009a) proposed to select sires whose daughters will cope better with low feeding levels and higher heat stress. They identified markers associated with sensitivity of milk production to feeding level and sensitivity of milk production to THI in Jersey and Holstein. Because feed-efficient animals are also more cost-effective and productive, the Australian beef industry now includes net feed efficiency as an integral part of its breeding programme (Beef CRC). Alford *et al.* (2006) calculated that CH_4 could be reduced by up to 16% in 25 years if residual feed intake (RFI) were included in beef selection programmes. Initial costs to identify individuals with low RFI are high, however, particularly in grazing animals (Arthur *et al.*, 2004). Because of the above-mentioned differences in feed quality, productivity improvements in pasture-fed ruminants in the tropics will result in higher relative CH_4 reductions than in ruminants grazing more digestible temperate pastures (McCrabb & Hunter, 1999). Possible synergies between plant and animal breeding need to

be better developed (FAO, 2008c).

Disease resistance

Experiments in domestic species have shown that there are often genetic differences in responses to disease challenge (Bishop *et al.*, 2002). Some of this variation is caused by single genes and some by multiple genes each with small effect. There is potential for genetic improvement of disease resistance, and various commercial breeding programmes already include resistance against helminthosis, ticks, mastitis, *E. coli* or scrapie. Extensive research on the genetics and breeding for worm resistance has been carried out in Australia, New Zealand and recently also in South Africa (de Greef, 2009). Breeding for disease resistance depends very much on the type of disease and the hosts' resistance or tolerance mechanisms, the availability and costs of alternative treatment (e.g. vaccines, drugs) and antimicrobial resistance of pathogens. In any case, the importance of molecular markers and marker assisted selection in such breeding programmes will increase (Bishop *et al.*, 2002; Prayaga *et al.*, 2006).

Challenges

The speed of artificial selection depends on many genetic factors, among others on reproductive technology, selection procedures and on the accuracy of phenotyping. Breeding for improved performance has become a high-tech exercise; the technologies and skills required present a bias towards certain breeds and production systems. Similarly, while GxE is the measure of choice for assessing variability of breed performance and adaptation across different environments, there are several caveats related to its wide application.

1. Limited breeds: On a routine basis, publicly accessible GxE across countries is only estimated for sires within 6 international dairy cattle breeds, through the international genetic evaluations

performed by Interbull that treat sire's multiple trait performance in each country as a different trait. Routine GxE assessments are not available for other cattle breeds or species.

2. Limited countries: Interbull's customers are mainly based in developed countries; South Africa is the only developing country customer. GxE effects are more pronounced if tropical countries are considered (Ojango & Pollott, 2002).

3. Limited production systems: Current AI bull evaluations are mainly based on daughters producing in high-input production systems and often do not differentiate between environments within countries (Zwald *et al.*, 2003). Even within the US dairy industry, GxE exists between husbandry systems and climatic zones, e.g. between grazing and confined dairy herds, especially those in extensive, hot areas (Kearney *et al.*, 2004).

4. Demanding data quality and analysis: Only a small percentage of national herds are usually used for progeny testing. Electronic data capture which increasingly forms the basis of genetic evaluations is mostly prevalent in large herds; in future even fewer herds will be needed for progeny testing. Adaptation traits are more difficult to study and to record, have lower heritability, higher levels of non-additive genetic variation and phenotypic variance, and are more susceptible to GxE than production traits (Frankham, 2009). Even in dairy cattle populations in some developed countries, female reproduction traits are incompletely recorded (Goddard, 2009) – not to mention other functional or adaptation traits.

5. Economic constraints: Although the genetic correlations between developed and developing countries are probably lower than 0.75 (Ojango & Pollott, 2002) – a threshold above which it is genetically reasonable to import semen from large breeding programs (Mulder *et al.*, 2006) – there are no breeding programmes in developed countries that target developing country environments. As only a relatively small amount of genetic material is sold to developing countries, commercial breeders find it hard to justify specific breeding programs for such environments.

The majority of developing countries import genetic progress in production traits rather than developing it in their local breeds, as was highlighted in the low number of breeding programmes reported in the FAO State of the World report (FAO, 2007a). Gollin et al. (2008) found that the more economically advanced developing countries are importers of genetic material, while the poorest countries are not engaged in any international trade in animal genetic resources. Only a few countries with well-developed breeding institutions, research, extension and artificial insemination services have commercially relevant tropical cattle breeds, tropically adapted taurine, zebuine or composites (e.g. Australia, Brazil, Kenya, South Africa, USA) and even fewer countries have commercially significant breeding programmes for adapted breeds of the other species (Madalena, 2008). This may strengthen the market position of commercial transboundary breeds in developing countries and indirectly continue to preclude characterization and selection within local breeds from these countries for increased production or even improved adaptation.

Genomic selection may exacerbate these trends, through the related requirements of reference populations for phenotyping. The accuracy of genomic breeding value estimation depends on the number of animals with phenotypes and genotypes in the reference population from which the SNP effects are estimated. Genomic selection is being applied in dairy breeding where consortia of main breeding companies are forming to assure the high numbers of progeny-tested bulls needed in the reference population. However, it is more difficult to implement in beef cattle or other ruminant species due to the dispersed breeding structure. In poultry, genomic selection is being tested across populations within companies (Avendano, 2009). A minimum of 500 progeny tested sires, with genotypes and full phenotypes recorded, are needed; this number can be reduced to 200-300 in breeds where the current genetic trend is close to zero (Ducrocq, 2010). Although costs for high-throughput genotyping have dropped considerably, genotyping and the phenotypic characterization and bioinformatics tools needed for their calibration are still most likely to be used in developed countries.

Genomic selection is promising but not yet transferable to developing countries where structured phenotyping and performance recording are largely missing and reference populations would be difficult to establish even if the genotyping could be sourced out. In order to be transferable across breeds or crossbreds, very high density SNP panels need to be developed and reference populations should include at least some individuals from all target breeds. The forthcoming 600K bead chip and improved imputation techniques will allow for better multi-breed analyses (Ducrocq, 2010). Also, GxE may reduce the accuracy of predicted genomic breeding value (Hayes *et al.*, 2009b) because linkage disequilibrium increases in adaptation to new environments (Frankham, 2009). Lillehammer *et al.* (2009) have developed a framework for evaluating effects of SNP in the presence of GxE, but this approach needs testing across a wide range of environments.

Conservation and exchange

Conservation

Conservation measures for threatened breeds have already been established in some countries (FAO, 2007a) and are a priority of the *Global Plan of Action for Animal Genetic Resources* (FAO, 2007b). The IPCC predicts an increase in disturbance and catastrophic weather events. Loss of animals as a result of droughts and floods, or disease epidemics related to climate change may thus increase (FAO, 2008a). If breeds are geographically isolated (endemic) – as is the case for some local and rare breeds – there is a risk of their being lost in localized disasters (Carson *et al.*, 2009). To secure against such disasters, it is necessary to characterize animal genetic resources and subsequently to build inventories, including information on the spatial distribution of breeds and valuable breeding stocks. This may include precautionary cryo-conservation of genetic material, or other measures to ensure genetic recovery following a disaster.

In the field of nature conservation and for crop wild relatives it is now argued that *in situ* strategies

have to account for the fact that conditions in species' historic ranges will change, and indeed are already changing (McCarty, 2001; Jarvis *et al*., 2008). Further to claims to facilitate species migration and maximizing adaptation opportunities through the maintenance of intact ecosystems, this results in a review of *in situ* conservation. However, recognizing that climate change may affect our food system quickly, the authors stress the urgent need to identify priority core species for collection and their inclusion in genebanks.

Similarly in animal genetic resources conservation, the focus may shift from *in vivo* to *in vitro* conservation. Most conservation programmes are based in developed countries with strong collaboration between genebanks and the animal breeding industry (FAO, 2007a). In developing countries, few breeds of the five major species are covered by conservation programmes, and programmes are of variable quality; the focus is typically on *in vivo* conservation (FAO, 2007a). Consequently, the sensitivity of *in situ* conservation programmes to the effects of climate change should be assessed and *ex situ* conservation measures be taken if needed. The role of the private genebanks held by breeding organizations or companies, and that of public genebanks still needs to be defined, but could involve the establishment of genebanks for local breeds and backups for commercial breeds. The operational protocols (e.g. material transfer agreements) remain to be developed.

Exchange

Most livestock production systems depend on species originally domesticated elsewhere and breeds developed in other countries and regions, making most countries highly interdependent with respect to animal genetic resources (FAO, 2007a,b). Climate change will increase the need to maintain wide access to animal genetic resources in the interests of future food security.

Livestock breeding and production systems are complex and knowledge intensive. New species or

breeds may replace the current ones as single new components in a production system or they may be changed together with other components of a system, including knowledge components. In human-managed systems, "establishment" of new species or breeds depends on how many components of the old production system can be transferred to the new area/system and on the socio-economic conditions. Blackburn & Gollin (2008) emphasize that successful introduction of new breeds into the USA has been based on several production traits and the interest and acceptance of the private sector, while introduction to take advantage of single traits has not proved sustainable, especially when other economically important traits were compromised. In any case, such replacement process may involve considerable costs and substantial investments in learning and gaining experience.

Although specific traits of tropical breeds may become important, it remains to be seen whether the impact of climate change will lead to a reassessment of the value of local breeds. The arguments Hill & Zhang (2009) make to explain why little use is made of conserved lines or breeds of developed countries to increase adaptation in commercial populations equally apply for local populations of developing countries: the production performance differentials between commercial, intensively selected breeds and any local breeds are so huge that selection for improved adaptation within those breeds offers far more opportunity than crossing or introgression of adapted genes. This is even more important as genomic selection will make better use of the genetic variation present in commercial populations. In any case it can be expected that only well-characterized breeds will be used for targeted crossing or gene insertion to increase the adaptedness of high-output breeds. However, most developing countries have insufficient resources or capacity for genetic or phenotypic breed characterization (FAO, 2007a).

Only if climate change exceeds the adaptive capacity of the currently used genetic portfolio, would countries need to depend on better-adapted genetic resources from other countries to adapt their

food and agriculture systems. In this case, increased strategic crossbreeding with better adapted breeds, or insertion of specific genes through the use of biotechnology, may occur (McManus *et al.*, 2008). The importance and value of specific genetics would thus increase. Such changes in the species or breed mix may potentially lead to a reverse in the current flow of genetics. Countries that happen to host sought-after resources may then try to take advantage of their scarcity and control access to what will have become crucial genetic resources. The need for improved exchange mechanisms for animal genetic resources and the associated knowledge would thus increase as well.

4. Conclusions

Climate change is one additional factor affecting the already highly dynamic livestock sector. However, due to its slow but long-term effect and more pressing current needs such as increasing demand for animal products, climate change is not yet fully on the radar screen of the livestock community. It will increase the need for resource-efficient livestock production and may thus intensify current trends with a growing dichotomy between livestock kept for livelihoods by smallholders and pastoralists, and those kept for commercial production. The direct effects of climate change depend very much on the production and housing system, resulting in a buffered effect for the high-output breeds in confined systems.

Climate change mitigation measures in conjunction with the "traditional" economic drivers may have implications of the breed portfolio. Measures that reduce the land area previously used for grazing may add to the threats to local ruminant breeds and affect the livelihoods of their keepers. Changes in the land area devoted to cropping (including fodder) relative to rangeland and their relative productivity will influence the balance between non-ruminant and ruminant production, as

will GHG reduction targets. In general, superior FCR will grant monogastrics a comparative advantage over cereal-fed ruminants. Efficiency differences between breeds will influence the proportion of commercial versus local breeds. High-output breeds of all species selected for improved FCR and high yield will dominate the production of milk, eggs and meat. These breeds will continue to out-compete local breeds. FAO (2007a) indicates that breed loss and risk in the past century was highest in regions that have the most highly-specialized livestock industries and in the species kept in such systems. The threat of extinction for local breeds, especially of monogastric species will increase. However, the outcomes of different scenarios and models imply different species or breed portfolios, making it difficult for decision makers to make rational choices.

Although many existing technologies in animal genetic resource characterization, conservation and breeding will be crucial for climate change adaptation and mitigation, research gaps exist, especially with regard to the physiology and genetics of adaptation. Research consortia such as GLOBALDIV have an important role to play in this regard. Currently, most research on the genetic variability of adaptation traits is undertaken with high-output breeds. There is need for long-term comprehensive breed characterization studies to shed light on the biological basis of adaptive traits.

At current state of knowledge, it is not predictable whether climate change will be faster than natural or artificial selection. Developed and developing countries differ with regard to their portfolios of genetic resources and the management of these resources. Most tropically adapted breeds reside in developing countries and are largely uncharacterized and without structured breeding or conservation programmes. On the other hand, most high-output breeds are selected for the requirements of developed country markets and production systems. Without support in breed characterization, breeding and conservation for developing countries, the divide between the scientific "haves" and "have-nots" will increase (OECD-FAO, 2009). Also the performance

differentials between local breeds and high-output breeds, the long-term commitment required for genetic improvement and the ease of genetic material imports may discourage developing countries from initiating their own breeding programmes. However, for the optimal utilization of the adaptation traits harboured in all breeds, research in genetic characterization and understanding adaptation in stressful environments needs to be strengthened. In view of the uncertainty for future developments, the use and non-use values of animal genetic resources should be maintained.

Agricultural biodiversity must be an integrated part of climate change adaptation and mitigation efforts. Especially in marginal areas, climate change adaptation, biodiversity conservation and poverty alleviation should complement each other (FAO, 2007b; FAO, 2008a,d). Strategies thus need to be developed that strengthen livestock keepers' adaptation strategies, their ecological knowledge and local institutions. The recent adoption by the international community of the *Global Plan of Action for Animal Genetic Resources* and the *Interlaken Declaration* provides for the first time an internationally agreed framework for the management of animal genetic resources, and also propose measures to support developing countries in their endeavours (FAO, 2007b).

comments on earlier versions of the paper. Content and errors are exclusively my responsibility.

The Author certifies that there is no conflict of interest regarding the material discussed in the

manuscript.

Table 1

Comparison of large-scale intensive and smallholder livestock production systems for a number of characteristics.

Defining Characteristics	large-scale, Intensive, often landless	Smallholder, mixed crop-livestock or pastoral
External input	high	low
Knowledge system	Scientific, global	Local, traditional
Species	pigs, chickens, dairy and beef cattle, turkeys; sheep to a lesser extent. Single-species operations.	all 33 species[1]. Multi-species and breed within species operations.
Products and services	milk, meat, eggs, fibre to a lesser extent	**Production-related services** milk, meat, eggs, wool & fibre, hides & skins, draught power & transport, fuel, manure for soil fertility **Socio-cultural services** insurance & asset function, dowry, religious ceremonies, risk management, medicinal purposes, cultural heritage, sports & entertainment, hobby & affection, status of owner, livelihoods **environmental service** waste conversion & use of crop-by products, weed & shrub control & fire management, seed dispersal, maintenance of cultural landscapes

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[1] FAO's Domestic Animal Information System DAD-IS covers 33 mammalian and avian livestock species: Alpaca, Ass, Bactrian Camel, Buffalo, Cassowary, Cattle, Chicken, Deer, Dog, Dromedary, Duck (domestic), Emu, Goat, Goose (domestic), Guanaco, Guinea fowl, Guinea Pig, Horse, Llama, Muscovy duck, Nandu, Ostrich, Partridge, Peacock, Pheasant, Pig, Pigeon, Quail, Rabbit, Sheep, Turkey, Vicuña, Yak (domestic)

Breeds	transboundary[2], with structured and "high-tech" breeding programmes	local, with traditional breeding systems
Environments	often protected (shelter, heating, cooling, filtered air)	unprotected (open grazing, scavenging)
Selection	high yield of specific market products in nutrient-rich environments	low yield of diverse products and services, "multi-functionality" in nutrient poor environments
Feed type	concentrates, cereals or highly digestible sown fodder	crop residues or indigenous, highly heterogeneous plant communities with variable nutritional value
Feed supply	Constant, adapted to current physiological needs ("precision feeding")	high seasonal variability
Disease control and biosecurity	vaccination, prophylaxis and treatment; high biosecurity	little or none

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[2] Local breeds are reported in only one country. Many recorded national breed populations occur in more than one country; these populations have been linked, and are referred to as "transboundary" breeds. Regional transboundary breeds are reported by several countries in one region, international transboundary breeds are reported by countries in several regions.

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