Section E

Animal genetic resources and adaptation

1 Introduction

The first report on *The State of the World's Animal Genetic Resources for Food and Agriculture* (first SoW-AnGR) (FAO, 2007) included a discussion of genetic resistance to, and tolerance of, diseases and parasites and the potential role of genetic diversity in disease control strategies.[1] This section updates the discussion presented in the first report, but also considers a broader range of adaptations important to the survival and productivity of animals in various production environments. The section is structured as follows: Subsection 2 summarizes the information on breed-specific (non-disease related) adaptations, recorded in the Domestic Animal Diversity Information System (DAD-IS);[2] Subsection 3 provides a discussion of non-disease related adaptations, based on the scientific literature; Subsection 4 provides an updated discussion of disease resistance and tolerance; and Subsection 5 presents some conclusions and research priorities.

2 Global information on adaptations

As described in Part 1 Section B, in the early 1990s FAO began to build up the Global Databank for Animal Genetic Resources, which now forms the backbone of DAD-IS. Along with data on population sizes, morphology, etc., DAD-IS allows countries to enter textual descriptions of their breeds' particular adaptations. To date, information of this kind has been provided only for a small number of the recorded breeds. This subsection provides an overview of the information on adaptations recorded in DAD-IS as of June 2014.

2.1 Adaptations at species and breed level

Bovines

A total of 139 breeds of buffalo are recorded in DAD-IS. Descriptions of their adaptations generally focus on their hardiness and adaptedness to high temperatures. The Anadolu Mandası of Turkey is known for its strong herd and maternal instincts and for protecting all the calves in the herd. The Chilika buffalo of India is known for its adaptedness to saline conditions.

Yaks have only a limited area of distribution – extending from the southern slopes of the Himalayas in the south to the Altai in the north and from the Pamir in the west to the Minshan Mountains in the east. They are found in cold, subhumid alpine and subalpine zones at elevations between 2 000 and 5 000 metres. In addition to its adaptedness to high elevations and cold climate, the species is recognized for its docility and hardiness. However, the records in DAD-IS provide little information about the specific adaptive characteristics of individual yak breeds.

Cattle have spread throughout the world and are found in almost all climatic zones, but not at high elevations. The most commonly reported breed-specific adaptations in this species are hardiness and

[1] FAO, 2007, Part 1 Section E (pages 101–112).
[2] http://fao.org/DAD-IS

adaptedness to heat and mountainous terrain (see Table 1E1).

Small ruminants

From a total of 681 reported goat breeds, 62 are reported to display adaptations to mountainous terrain. In general, this includes jumping ability, flexible hooves and tolerance of poor nutrition. In addition, 30 goat breeds were reported to be heat tolerant, 7 tolerant of humidity, 14 cold tolerant, 11 adapted to extreme diets, 20 adapted to water scarcity and 20 adapted to dry environments.

Like goats, sheep are frequently well adapted to harsh environments (see Table 1E2). However, the only two sheep breeds recorded in DAD-IS as being well adapted to humid environments

TABLE 1E1

Adaptations in cattle breeds as recorded in DAD-IS

Region	Number of breeds*	Heat	Cold	Humidity	Extreme diet	Water scarcity	Mountainous terrain	Dry environment	General hardiness
Africa	212	32	0	7	1	8	2	20	51
Asia	261	40	12	2	12	4	22	6	24
Southwest Pacific	399	8	0	0	0	2	0	0	1
Europe and the Caucasus	147	28	17	2	13	2	79	9	94
Latin America and the Caribbean	44	12	3	0	3	2	9	8	11
North America	19	2	0	0	0	1	0	1	2
Near and Middle East	33	3	0	1	0	5	1	3	2
World	**1 115**	**125**	**32**	**12**	**29**	**24**	**113**	**47**	**185**

Note: *Excluding extinct and international transboundary breeds.
Source: DAD-IS accessed in March 2014.

TABLE 1E2

Adaptations in sheep breeds as recorded in DAD-IS

Region	Number of breeds*	Heat	Cold	Humidity	Extreme diet	Water scarcity	Mountainous terrain	Dry environment	Docility
Africa	141	9	5	1	0	10	3	17	3
Asia	276	36	25	1	4	4	35	13	7
Southwest Pacific	687	0	3	0	0	0	1	0	0
Europe and the Caucasus	54	23	22	0	15	3	108	16	34
Latin America and the Caribbean	57	2	1	0	1	0	3	2	1
North America	27	2	1	0	0	0	0	0	2
Near and Middle East	41	11	0	0	1	4	1	7	7
World	**1 283**	**83**	**57**	**2**	**21**	**21**	**151**	**55**	**54**

Note: *Excluding extinct and international transboundary breeds.
Source: DAD-IS accessed in March 2014.

are the Djallonké of Guinea and the Xinjiang Finewool of China.

Camelids

The alpaca and the llama inhabit Andean rangelands at elevations of up to 5 000 metres above sea level. They thrive in a wide range of climates and on very poor pastures. Worldwide, eight breeds of alpaca and six breeds of llama are recorded in DAD-IS (see Part 1, Section B Figure 1B6). No particular differences in adaptedness between these breeds are reported. Bactrian camels are described as hardy, tolerant to heat, dry environments and water scarcity. All 14 reported breeds are described as being well adapted to desert conditions, extreme temperature ranges and shortages of water and food. They have the ability to rapidly gain and store large amounts of fat. Dromedaries are reported from a wide geographical area, ranging from the Atlas Mountains of northwestern Africa to the Australian outback. The majority of reported adaptations relate to tolerance of water scarcity or dry environments or to general hardiness. It is reported that the Rendille camel breed of Kenya can be kept for up to 14 days without water. The Chameau du Kanem and Gorane breeds of Chad are reported to be adapted to consumption of salt water.

Equines

Equines are found in all climatic zones. Special adaptations are documented only for a relatively small number of the 174 reported ass breeds and the 905 reported horse breeds (see Table 1E3). Horses are mostly described as being hardy and well adapted to mountainous terrain. A very few breeds (e.g. the Sunico Pony of the Plurinational State of Bolivia and the Tibetan horse) are reported to be adapted to high elevations.

Pigs

Of the 709 pig breeds reported worldwide, 63 breeds are described as being especially hardy. Special adaptedness to heat is reported for 27 breeds, to extreme diets for 11 breeds, to cold for 6 breeds and to dry environments for 7 breeds. China reports four pigs breeds adapted to a cold climate, the Bamei, Harbin White, Sanjiang White and Min. By developing layers of fat and growing thick hair during the winter, they are able to thrive in cold environments. However, this slows their growth rate in comparison to other breeds.

Chickens

Chicken breeds are kept in all geographic regions. The most commonly reported adaptations are hardiness and heat tolerance. Switzerland reports that the Appenzeller Barthuhn, with its characteristic beard and small rose comb, is resistant to cold. A wide spectrum of behavioural traits are reported. Some breeds are known for their docility and others for their fighting ability.

3 Adaptation to non-disease stressors

3.1 Introduction

One of the key features of animal genetic diversity is that it enables livestock to be kept in a wide

TABLE 1E3

Adaptations in equine breeds as recorded in DAD-IS

Species	Number of breeds*	Heat	Cold	Extreme diet	Water scarcity	Mountainous terrain	Dry environment	General hardiness
Ass	174	2	3	1	5	-	7	14
Horse	905	9	6	7	2	30	4	77

Note: *Excluding extinct and international transboundary breeds.
Source: DAD-IS accessed in March 2014.

range of production environments. As a result of natural selection, livestock populations tend, over time, to acquire characteristics that facilitate their survival and reproduction in their respective production environments. In other words, they become adapted to local conditions. Because livestock are domesticated animals that are managed by humans, the process of adaptation is complicated by, *inter alia*, the effects of artificial selection, management interventions that alter production environments and the movement of animals or germplasm from one production environment to another. Capacity to isolate animals from the stressors present in the local environment – extremes of temperature, feed shortages, diseases, etc. – has increased over the years, but the conditions in which animals are raised continue to be very diverse. Particularly in smallholder and pastoralist systems, animals often face harsh production conditions and have to rely on their adaptive characteristics.

3.2 Adaptation to available feed resources

Animals that are well adapted to coping with periods of feed scarcity may have one or more of the following characteristics: low metabolic requirements; the ability to reduce their metabolism; digestive efficiency that enables them to utilize high-fibre feed; and the ability to deposit a reserve of nutrients in the form of fat.

Having low metabolic requirements helps an animal to survive if feed is in short supply or is of poor quality. One breed that has been found to show this characteristic is the Black Bedouin goat, a small desert breed native to the Near East (Silanikove, 1986a; 2000). The energy requirement of a mammal is normally considered to be a function of its body mass raised to the power of 0.75. This implies that energy requirement per kilogram of body tissue is greater in small mammals than in larger ones and that smaller animals will have to compensate for this by eating more and/or higher-quality feed. Thus, in theory, the total energy requirements of five 20 kg Black Bedouin goats total metabolic weight = 20 $kg^{0.75}$ x 5 = 47.3 kg) should be considerably higher than that of a single large European goat weighing 100 kg (metabolic weight = 100 $kg^{0.75}$ = 31.6 kg). In fact the total requirements are similar (Silanikove, 2000).

Some mammals are able to maintain steady body weights even if their energy intakes are below voluntary intake levels. This may be due to an ability to reduce metabolism. For example, Silanikove (2000) compared the abilities of non-desert Saanen goats and Bedouin goats fed on high-quality roughages to maintain steady body weights when their consumption was restricted. The Saanen goats were able to cope with a 20 to 30 percent reduction relative to their voluntary intakes. The Bedouin goats tolerated a 50 to 55 percent reduction. The Bedouin animals had a 53 percent lower fasting heat production under feed restriction. Other herbivores that are annually exposed to long periods of severe nutritional restriction in their native habitats (e.g. zebu cattle and llamas) also possess a similar capacity to adjust to low energy intake by reducing their energy metabolism (ibid.).

Ruminants are known for their ability to utilize high-fibre feed. Goats can digest high-fibre low-quality forages more efficiently than other ruminants; one of the main reasons for this is a longer mean retention time of feed in the rumen (Devendra, 1990; Tisserand *et al.*, 1991). Goat breeds indigenous to semi-arid and arid areas are able to utilize low-quality high-fibre feed more efficiently than other goats (Silanikove *et al.*, 1993). For example, the digestive efficiency of Black Bedouin goats fed on roughage diets has been shown to be superior to that of Swiss Saanen goats (Silanikove *et al.*, 1993; Silanikove 1986a; Brosh *et al.*, 1988).

Ability to store energy in adipose tissues when sufficient feed is available and subsequently to mobilize it during periods of scarcity is an important adaptation for animals that have to cope with fluctuating feed supplies (Ball *et al.*, 1996; Ørskov, 1998). Negussie *et al.* (2000) found that in the Menz and Horro fat-tailed sheep breeds of Ethiopia, tail and rump fat depots were the most readily utilizable in the event of feed shortages.

Ermias *et al.* (2002) reported an encouraging heritability estimate (0.72±0.19) for the combined weight of tail and rump fat in Menz sheep, indicating opportunities for selective breeding.

In addition to adaptations related to feed shortages and the use of high-fibre forages, some breeds of livestock have developed unique physiological abilities that enable them to survive on unusual feed resources. For example, the North Ronaldsay, a breed of sheep native to an island off the coast of Scotland, in the United Kingdom, survives on a diet consisting mainly of the seaweed *Limnaria* (NCR, 1993). It can cope with a diet that is very low in copper and in which some elements (e.g. sodium) are present in excess. Other breeds found in Scotland, which normally feed on grass or hay, would die from lack of copper if fed on *Limnaria*.

3.3 Adaptation to extreme temperatures

When animals are exposed to heat stress, their feed intakes decrease and they suffer metabolic disturbances (Marai *et al.*, 2007). This, in turn, impairs their productive and reproductive performance. The effects are aggravated when heat stress is accompanied by high humidity. Differences in thermal tolerance exist between livestock species (ruminants are more tolerant than monogastrics), between breeds and within breeds (Berman, 2011; Caldwell, *et al.*, 2011; Coleman, *et al.*, 2012; Renaudeau *et al.*, 2012; Menéndez-Buxadera *et al.*, 2012). For example, McManus *et al.* (2009a) compared physiological traits (sweating, respiratory and heart rates, rectal and skin temperatures) and blood parameters (packed cell volume, total plasma proteins, red blood cell count, and haemoglobin concentration) in different sheep populations in Brazil: the Santa Inês (a hair sheep with three different coat colours – brown, black and white), the Bergamasca (a wool sheep) and Santa Inês × Bergamasca crosses. The study found that there were significant differences between animals due to breed and skin type, and concluded that the white-coloured Santa Inês animals were the best adapted to high temperatures and that the Bergamasca were the least well adapted. The genetic correlation between milk production and heat tolerance in sheep is reported to be negative (Finocchiaro *et al.,* 2005), indicating that selection for increased milk production will reduce heat tolerance.

The adaptedness of zebu cattle to hot climates is related to the characteristics of their coats, hides and skins, as well as to their haematological characteristics and to their form, growth and physiology (Turner, 1980). Zebu cattle are smooth coated, have better-developed sweat and sebaceous glands than taurine cattle (ibid.). McManus *et al.* (2009b) compared parameters related to heat tolerance in seven cattle breeds (including zebu and taurine breeds and breeds considered exotic and locally adapted to Brazilian conditions) and found the zebu Nelore to be the best adapted to heat stress and the taurine Holstein to be the least well adapted.

Adaptation to cold (see Box 1E1) involves a number of different mechanisms. For example, a long thick hair coat contributes to thermal insulation. Sheep originating from and living in cold areas deposit more of their body fat under the skin than those adapted to warmer areas (Kempster, 1980; Farid, 1991; Bhat, 1999; Negussie *et al.*, 2000; Ermias *et al.*, 2002). In many sheep adapted to arid conditions, almost all fat is deposited on the rump and/or in the tail (Bhat, 1999). This helps the animals avoid thermal stress, as these deposits do not greatly impede heat loss from the body. Studies of the Horro and Menz sheep breeds of Ethiopia (Negussie *et al.,* 2000; Ermias *et al.,* 2002) have shown that, in the former, a large proportion of total body fat is deposited in the rump and tail, while subcutaneous and intramuscular deposits predominate in the latter. The production environment of the Menz is cooler than that of the Horro, which lives at a slightly lower elevation.

3.4 Adaptation to water scarcity

Breeds of ruminants native to arid lands are able to withstand prolonged periods of water deprivation and can graze rangelands where watering sites are 50 km or more far apart (Silanikove, 1994; Bayer and Feldmann, 2003). Livestock that

Box 1E1

Yakutian cattle – a breed well adapted to subarctic climatic conditions

The Yakutian cattle of the Sakha Republic in the Russian Federation, a unique population of Turano-Mongolian type *Bos taurus*, are believed to be the last remaining indigenous Siberian cattle. They are dual-purpose animals (milk and meat) and have small but strong bodies, small firm udders and short firm legs. Their bodies and teats are covered with thick hair. They are well adapted to the extreme environment and climate of the subarctic region, characterized by long, dark and cold winters, during which the temperature can fall to -60 °C. They are capable of thriving on the poor feed provided by the plants of the northern environment and require less body maintenance energy during winter than other cattle. They grow and fatten rapidly during the short summer. They are reported to be resistant to tuberculosis, leucosis and brucellosis. They have a long productive life, some cows living for more than 20 years and calving more than ten times.

Sources: Ovaska and Soini, 2011; Li *et al.*, 2012.

Photo credit: Anu Osva (previously published in Granberg et al., *2009, reproduced with permission).*

need little water and do not have to go back to a watering point every day can access larger areas of pasture and thus obtain more feed during periods of drought. For example, dromedaries can survive up to 17 days of water deprivation when consuming dry food in hot conditions or can go without drinking water for 30 to 60 days when grazing on green vegetation (Schmidt-Nielsen, 1955; Schmidt-Nielsen *et al.*, 1956). There are also donkey, goat, sheep and cattle breeds that can go without drinking for several days (Bayer and Feldmann, 2003). Such animals drink large amounts of water quickly, but their overall water intake is lower than that of animals that are watered daily. Reduced water intake reduces feed intake and metabolic rate, and animals can therefore survive for longer when feed is scarce. Desert goats are reported to be the ruminants that have the greatest ability to withstand dehydration (Silanikove, 1994). For example, the Black Bedouin goat of the Near East and the Barmer goat of India often drink only once in every four days (Khan *et al.*, 1979a,b,c; Silanikove, 2000). Bedouin goats are also able to maintain a good level of milk production under water deprivation. The basis of these breeds' ability to cope with severe water shortages is their ability to withstand dehydration and to minimize water losses via urine and faeces. By the fourth day of dehydration, the water losses of Barmer and Bedouin goats may exceed 40 percent of their body weights (Khan *et al.*, 1979a,b; Silanikove, 2000).

3.5 Adaptation to interaction with humans

The process of domestication (see Part 1 Section A) involved adaptation to human management. Domesticated animals are more docile than their wild ancestors and less fearful of humans. Nonetheless, routine management procedures (e.g. shearing, castration, tail docking, dehorning, vaccination, herding and transportation) can still trigger fear and thereby negatively affect animal welfare (Boissy *et al.*, 2005). Excessive fear can also reduce productivity. For instance, fear-related reactions affect sexual and maternal behaviours in cattle and sheep. Estimates of the heritability of fear range between 0.09 and 0.53 in dairy cattle and between 0.28 and 0.48 in sheep; a moderate heritability of 0.22 has been estimated for reactions to handling in beef cattle (ibid.). Thus, selection based on reduced fearfulness could have a significant influence on the welfare of ruminant livestock.

3.6 Adaptation to predators

Domesticated animals express less vigorous anti-predator behaviour than their wild counterparts, probably because human protection has reduced selection pressure for anti-predator traits. There is some evidence of between-breed differences in antipredator behaviour. Hansen *et al.* (2001) compared the responses of light, medium-weight and heavy sheep breeds to the presence of predator-related stimuli (leashed dogs or stuffed wild predators on trolleys) and found that the light breeds displayed stronger antipredator reactions (longest flight distance, tightest flocking behaviour and longest recovery time). A more recent study suggested that this response to predator-like stimuli could explain, at least partially, the improved survivability of free-ranging lambs in light breeds (Steinheim *et al*., 2012).

4 Disease resistance and tolerance

4.1 Introduction

Diseases are one of the major constraints to livestock productivity and profitability worldwide. A range of disease-control options exist, including chemical or biological treatments, vaccination and preventive management. Each of these approaches has its strengths, weaknesses and limitations. Another option is to utilize genetic approaches, which can serve either to substitute or to complement other disease-control strategies.

Evidence of genetic influence on disease susceptibility has been reported for many animal diseases (e.g. Bishop and Morris, 2007; Gauly *et al*., 2010). Advantages of genetic approaches to disease control include the long duration of the effect, the possibility of broad spectrum effects (resistance to more than one disease) and the possibility of using genetics in concert with other approaches (FAO, 1999). In addition, genetic changes should, theoretically, be less subject to pathogen resistance, as they will often be the result of relatively small effects at many genes, none of which alone will be sufficient to drive a genetic response in the pathogen (Berry *et al.*, 2011). Two concepts need to be distinguished in this context: "resistance" refers to the ability of the host to control infection by a given pathogen, whereas "tolerance" refers to the ability of the host to mitigate the adverse effects of the pathogen once infection occurs.

Genetic management of disease can involve a number of different strategies, including breed substitution, cross-breeding and within-breed selection. The appropriate choice of strategy will depend on the disease, the production environment and the resources available. Within-breed selection can be facilitated if molecular genetic markers associated with the desired traits have been identified (CABI, 2010).

Whatever strategy is chosen, genetic diversity in the targeted livestock populations is a necessary precondition. If genetic resources are eroded, potentially important means of combating disease may be lost. Maintaining multiple breeds increases the options available for matching breeds to production environments, including the disease challenges present in these production environments. Maintaining within-breed diversity allows for individual selection. Even where genetic strategies are not immediately required in order to combat current animal health problems, maintaining diversity in the genes underlying resistance means maintaining an important resource for combating the effects of possible future pathogen evolution. Furthermore, at individual animal level, increased genetic diversity may allow for a more robust immune response to a wider range of pathogen strains and species. A recent study of African cattle reported an association between genetic diversity (as measured by molecular heterozygosity) and lower incidence, and higher survival, of infectious diseases (Murray *et al*., 2013).

This subsection serves as an update of the discussion of the genetics of disease resistance and tolerance presented in the first SoW-AnGR.[3] In addition to presenting the latest data available

[3] FAO, 2007, Part 1 Section E (pages 101–112).

in DAD-IS on breeds' resistance and tolerance to specific diseases, it briefly discusses recent scientific developments in this field and their potential significance for disease-control strategies, focusing particularly on research findings published since the first SoW-AnGR was prepared. The discussion generally emphasizes diseases for which breed-level resistance or tolerance has been reported to DAD-IS, although research results for other diseases are also cited.

4.2 Disease resistant or tolerant breeds

In theory, breeds that have been present an extended period of time in an area where a given disease is endemic may develop genetic resistance or tolerance to that disease. This is because natural selection should favour the accumulation of alleles associated with greater survival. In the case of many common livestock diseases, evidence is available in the scientific literature that some breeds are more resistant or tolerant than others. A number of examples, drawn from recent (i.e. after 2006) studies are presented in Table 1E4. The information entered by countries into DAD-IS includes many anecdotal reports of such adaptations. Table 1E5 presents an overview of the entries in DAD-IS that report disease resistance or tolerance in mammalian breeds. Tables 1E6 to 1E12 list breeds reported to be resistant or tolerant to specific diseases or disease types. In most of these cases, the claims made for specific breeds have not been subject to scientific investigation.

Few new reports of breeds with resistance or tolerance to specific diseases have been entered into DAD-IS since 2007. New examples have generally been from countries that have undertaken comprehensive characterization studies for the first time. However, many more cases of general disease resistance have been reported. In addition, a great deal of research has been undertaken to substantiate anecdotal evidence and uncover the biological mechanisms associated with differences among breeds in terms of their susceptibility to common livestock diseases. Recent scientific developments with respect to the main diseases featured in the DAD-IS data – including several that did not feature in the discussion presented in the first SoW-AnGR – are briefly discussed in the following subsections. Short discussions are also presented for some diseases for which no information on breed resistance has been entered into DAD-IS, but for which information is available in the scientific literature.

Trypanosomosis

Tsetse-transmitted trypanosomosis remains a serious and costly disease throughout West, Central and, to a lesser extent, East Africa, despite multifaceted attempts to control it. Although trypanocidal drugs can be useful, parasite resistance to these drugs increases yearly. Fortunately, locally adapted breeds of ruminants in areas of high tsetse fly challenge show consistent tolerance to this disease. Table 1E6 contains a full list of breeds recorded in DAD-IS as being trypanotolerant or resistant. As was the case at the time the first SoW-AnGR was prepared, the most commonly reported trypanotolerant breeds are N'Dama cattle and Djallonké sheep and goats (also known as West African Dwarf or under other names, depending on the country). Since the time of the first SoW-AnGR, information on trypanotolerant cattle, sheep and goats breeds has been recorded in DAD-IS by Sudan and information on trypanotolerant pigs and equines by several West and Central African countries.

Various studies have been undertaken in recent years to elucidate the biological basis for trypanotolerance (e.g. O'Gorman *et al.*, 2009; Stijlemans *et al.,* 2010; Noyes *et al.*, 2011). Two physiological mechanisms seem to be involved: 1) increased control of parasitaemia; and 2) greater ability to limit anaemia (Naessens *et al.*, 2006). One group of scientists is currently attempting to use genetic modification to create a trypanosome-resistant strain of cattle, based on a genetic mechanism present in baboons and some human populations (Willyard, 2011).

TABLE 1E4

Examples of studies indicating breed differences in resistance, tolerance or immune response to specific diseases

Disease/parasite	Breed(s) or genotype(s) showing the favourable phenotype	Compared to which breed(s) or genotype(s)	Experimental conditions	Results	Reference
Theileria annulata	Sahiwal cattle	Holstein	Artificial infection of isolated monocytes	Less severe clinical signs in the Sahiwal, gene expression profile of monocytes differs between the two breeds	Glass and Jensen, 2007
Trypanosomosis	N'Dama × Kenya-Boran cattle	Kenya-Boran	Field challenge	N'dama cross-breed more trypanotolerant, especially females	Orenge *et al.*, 2012
Tuberculosis	Zebu cattle	Holstein	Natural and artificial infection	Zebu have fewer clinical signs and decreased morbidity	Ameni *et al.*, 2007; Vordermeier *et al.*, 2012
Fasciola gigantica	Buffalo	Ongole cattle	Artificial infection	Buffalo have 1/5 the number of flukes Ongole cattle have	Wiedosari *et al.*, 2006
Rhipicephalus microplus	Nguni cattle	Bonsmara	Natural infection	Leukocyte profile differs between infected Nguni and Bonsmara	Marufu *et al.*, 2011
Rhipicephalus microplus	Braford, Brangus, Nelore cattle	Charolais	Natural infection	Fewer ticks carried by the Braford, Brangus and Nelore	Molento *et al.*, 2013
Haemonchus contortus	Caribbean hair sheep	Wool sheep	Artificial infection	Caribbean Hair sheep have higher PCV, lower FEC, higher IgA than the wool sheep	MacKinnon *et al.*, 2010
Haemonchus contortus	Gulf Coast Native sheep	Suffolk	Pasture-based infection	Native lambs have more robust immune response to infection	Shakya *et al.*, 2009
Fasciola gigantica	Indonesian Thin Tail sheep	Merino	Artificial infection	Type1 immune response makes Indonesian Thin Tail more resistant	Pleasance *et al.*, 2011
Porcine reproductive and respiratory syndrome (PRRS)	Miniature pigs	Pietrain pigs	Artificial infection	Virus replication in the miniature pigs only 3.3% of that in the Pietrain	Reiner *et al.*, 2010
PRRS	Meishan pigs	Duroc, Hampshire	Artificial infection	Meishan have less PRRS antigen in their lungs	Xing *et al.*, 2014
Marek's disease	Erlang Mountain chickens	Commercial broiler	Artificial infection	Erlang show reduced clinical signs and faster clearance of virus	Feng *et al.*, 2013
Infectious bursal disease virus	Aseel chickens	Commercial	Artificial infection	TH1 immunity, upregulation in the Aseel	Raj *et al.*, 2011
Avian influenza	Fayoumi chickens	Leghorn	Artificial infection	Resistance to infection in the Fayoumi	Wang *et al.*, 2014
Newcastle disease	Naked-neck chickens	Frizzle- and smooth-feathered chickens	Artificial infection	Naked-neck shows lower mortality	Bobbo *et al.*, 2013

Note: FEC = faecal egg count; PCV = packed cell volume; IgA = immunoglobulin A; TH1 = type 1 T helper cell.

TABLE 1E5

Number of mammalian breed populations recorded in DAD-IS as having resistance or tolerance to specific diseases or parasites

Disease/parasite	Number of reported resistant or tolerant breed populations* per species							
	Buffalo	Cattle	Goats	Sheep	Pigs	Horses	Deer	Camelids
Unspecified	8	74	22	32	27	36		1
Trypanosomosis		48	22	18	2	3		
Tick infestation/burden	1	24		5			1	
Tick-borne diseases (unspecified)	1	26	1	5			1	
Anaplasmosis		2						
Piroplasmosis/babesiosis						1		
Heartwater/cowdriosis		2		2				
Theileria		2						
Internal parasites	3	1	2	16	1	3	1	
Fascioliasis		1						
Bovine leukosis		11		1				
Foot rot		1		13				
African swine fever					6			
Tuberculosis		13	3	1				
Brucellosis	1	7	3	2				
Foot-and-mouth disease	2	1						
Total	**16**	**236**	**54**	**94**	**36**	**43**	**3**	**1**

Note: *"Breed population" = a given breed within a given country.
Source: DAD-IS accessed in March 2014.

Ticks and tick-borne diseases

Ticks continue to cause disease and production loss throughout the world, most notably in tropical and subtropical areas. Tick infestation causes blood loss and decreased milk or meat production. Ticks also transmit a number of diseases, including babesiosis, anaplasmosis and cowdriosis. Some breeds of cattle are reported to be resistant to tick infestation and tick-borne disease. There are several potential explanations for the greater resistance of some breeds to tick infestation, including their coat characteristics, skin sensitivity, grooming behaviour and degree of inflammatory response (Mattioli *et al.*, 1995; Marufu *et al.*, 2011; Mapholi *et al.*, 2014). Tables 1E7 and 1E8 show the breeds recorded in DAD-IS as being resistant to, or tolerant of, tick infestation and/or tick-borne diseases.

Recent findings suggest that susceptibility and resistance to tick infestation may be related to differences in the types of immune responses that occur in susceptible and resistant animals. Marufu *et al.* (2014) report that an increased immune response involving basophils, monocytes and mast cells was noted in resistant Nguni cattle, whereas in susceptible animals, neutrophils and eosinophils were the primary cellular responders to tick bite. Increased neutrophil concentrations were hypothesized to facilitate the distribution of tick-borne pathogens within infected hosts, as enzymes that they release compromise the extracellular matrix. Mast cells and basophils,

TABLE 1E6

Breeds recorded in DAD-IS as showing resistance or tolerance to trypanosomosis

Species	Region/subregion	Number of breeds	Most common name of breed
Cattle	North and West Africa	15	N'Dama (20), Lagune (Lagoon) (6), Baoulé (4), Borgou/Ketuku (3), Somba (2), Muturu (2), Dahomey (Daomé), Ghana Shorthorn, Kapsiki, Kuri, Namchi, Toupouri
	East Africa	2	Jiddu, Shekko
	Southern Africa	2	N'Dama, Dahomey (Daomé)
	Near and Middle East	1	Nuba Mountain
Sheep	North and West Africa	2	Djallonké (West African Dwarf) (13), Vogan (2)
	Near and Middle East	3	Mongalla, Nilotic, Nuba Mountain Dwarf
Goats	North and West Africa	1	Djallonké (West African Dwarf) (20)
	Near and Middle East	2	Nilotic, Yei
Pigs	West Africa	2	Local Pig of Benin, Nigerian Native
Horses	North and West Africa	2	Bandiagara (2), Poney du Logone

Note: Figures in brackets indicate the number of countries (if more than one) reporting that the breed is resistant or tolerant.
Source: DAD-IS accessed in March 2014.

on the other hand, increased immune response in the area of the bite, in addition to promoting grooming behaviours that promote tick removal. Although further research is needed, greater understanding of the immunological basis for between-breed differences in resistance may facilitate the development of more effective control strategies.

Internal parasites

Helminthosis continues to cause major production losses throughout the world, particularly as parasite resistance to anthelminthic drugs increases. This latter development places additional pressure on livestock keepers and governments to rely more heavily on genetically resistant or tolerant breeds for production in parasite-infested areas. Breeds noted in DAD-IS as having some resistance to internal parasites are listed in Table 1E9. Many breeds of small ruminants have been characterized as parasite resistant (González *et al.*, 2012).

As described in the first SoW-AnGR, the Red Maasai sheep of Kenya is noted for its resistance to the parasite *Haemonchus contortus.* Direct breed comparison studies have shown lower faecal egg counts in Red Maasai than in Dorper lambs (Baker *et al.,* 2004). A more recent study of specific quantitative trait loci in cross-bred animals found that all favourable alleles were associated with the Red Maasai (Marshall *et al.*, 2013). Recent studies have also indicated that the Thalli sheep of Pakistan shows significant resistance to *Haemonchus contortus* infection and lower levels of anaemia during infection than other Pakistani breeds (Babar *et al.*, 2013). Similarly, Santa Ines ewes (a Brazilian breed) have been found to be more resistant than Ile de France ewes when challenged with this parasite (Rocha *et al.*, 2011). Since the first SoW-AnGR was prepared, a number of within- and across-breed genomic studies have been undertaken (e.g. Riggio *et al.*, 2013).

The first SoW-AnGR noted that resistance to *Fasciola gigantica* had been reported in Indonesian Thin Tail sheep. Since that time, researchers have confirmed that this resistance is quite pathogen specific and does not extend to other liver flukes such as *F. hepatica* (Pleasance *et al.*, 2010). There are indications that the resistance is based on an early type 1 innate immune

TABLE 1E7

Breeds recorded in DAD-IS as showing resistance or tolerance to tick burden

Species	Region/subregion	Number of breeds	Most common name of breed
Cattle	Southern Africa	10	Nguni (2), Bonsmara, Kashibi, Nandi, Pedi, Shangaan, Sul do Save, Tswana, Tuli, Venda
	Southeast Asia	6	Australian Milking Zebu, Droughtmaster, Java, Local Indian Dairy Cow, Pesisir, Thai
	Europe and the Caucasus	1	Zebu of Azerbaijan
	South America	1	Romosinuano
	Southwest Pacific	5	Australian Charbray, Australian Friesian Sahiwal, Australian Milking Zebu, Australian Sahiwal, Javanese Zebu
Sheep	Southern Africa	3	Nguni (3), Landim, Pedi
Buffalo	Southeast Asia	1	Krabue
Deer	Southeast Asia	1	Sambar

Note: Figures in brackets indicate the number of countries (if more than one) reporting that the breed is resistant or tolerant.
Source: DAD-IS accessed in March 2014.

TABLE 1E8

Breeds recorded in DAD-IS as showing resistance or tolerance to tick-borne diseases

Species	Region/subregion	Diseases	Number of breeds	Most common name of breed
Cattle	North and West Africa	Tick-borne (unspecified)	3	Baoulé (3), Ghana Shorthorn, Sahiwal,
		Piroplasmosis	1	Noire Pie de Meknès
	East Africa	Tick-borne (unspecified)	2	Sahiwal (2), Nandi
	Southern Africa	Piroplasmosis	3	N'Dama, Nguni, Sahiwal
		Theileria	1	Angoni
	Europe and the Caucasus	Piroplasmosis	3	Cinisara, Modicana, Southern Beef
		Anaplasmosis	2	Cinisara, Modicana
		Heartwater (cowdriosis)*	1	Creolé (2)
	East Asia	Theileria	1	Jeju Black cattle
	South Asia	Tick-borne (unspecified)	2	Sahiwal (5), Local Indian Dairy Cow
	Southeast Asia	Tick-borne (unspecified)	1	Sahiwal (4)
	Caribbean	Tick-borne (unspecified)	1	Sahiwal (2)
	South America	Tick-borne (unspecified)	1	Creole (2), Sahiwal
	Southwest Pacific	Tick-borne (unspecified)	1	Sahiwal
Sheep	Southern Africa	Heartwater (cowdriosis)	1	Damara (2)
Horses	Europe and the Caucasus	Piroplasmosis	1	Pottok

Note: *These reports are from the French overseas territories of Guadeloupe and Martinique, i.e. not geographically from the Europe and the Caucasus region. Figures in brackets indicate the number of countries (if more than one) reporting that the breed is resistant or tolerant.
Source: DAD-IS accessed in March 2014.

TABLE 1E9
Breeds recorded in DAD-IS as showing resistance or tolerance to internal parasites

Species	Region/subregion	Number of breeds	Most common name of breed
Cattle	Southern Africa	1	Madagascar Zebu
Goats	Southeast Asia	1	Kacang
	East Asia	1	Tokara
Sheep	Southern Africa	1	Kumumawa
	Northern Africa	1	Rahmani
	Southeast Asia	2	Garut, Malin
	Europe and the Caucasus	1	Solognot
	Latin America and the Caribbean	3	Criollo (9), Morado Nova, Priangen
Horse	Southeast Asia	2	Bajau, Kuda Padi
	South America	1	Peruano de Paso
Deer	Southeast Asia	1	Sambar

Note: Figures in brackets indicate the number of countries (if more than one) reporting that the breed is resistant or tolerant.
Source: DAD-IS accessed in March 2014.

response.[4] A response of this kind is hypothesized to be effective only against *F. gigantica,* which develops more rapidly than *F. hepatica* (Pleasance *et al.*, 2011). In molecular and biochemical terms, infections with *F. gigantica* and *F. hepatica* elicited different responses in the Indonesian Thin Tail sheep. Immunological responses to *F. gigantica* also differed between Indonesian Thin Tail sheep and Merino sheep (a non-resistant breed).

Foot-and-mouth disease

Foot-and-mouth disease is a highly contagious viral disease of cloven-hooved animals. A vaccine exists, but the disease is also controlled by tight restrictions on the movement of animals from affected to non-affected countries and in some countries by culling programmes in the event of an outbreak. Two buffalo and one cattle breed have been declared in DAD-IS to show some level of resistance to this disease. These reports have yet to be substantiated in the scientific literature.

Bovine leukosis

Bovine leukosis occurs in a proportion of cattle infected with the bovine leukosis virus (BLV). Although not all animals infected with the virus become clinically affected, the condition causes significant losses in production and increased mortality. Evidence of breed-based resistance to clinical leukosis is scant and primarily anecdotal. Reports of resistance are limited to breeds from Central Asia and the Russian Federation (see Table 1E10). However, research on some common international transboundary dairy breeds has indicated a genetic basis for susceptibility to the disease (Abdalla *et al.*, 2013). Research regarding the molecular explanation of resistance suggests that imbalances in certain receptors (tumor necrosis factor alpha in particular) can contribute to increased susceptibility (Konnai *et al.*, 2005).

[4] Immune responses to infectious diseases comprise types 1 and 2. The two types differ according to the cells involved (T helper 1 vs. T helper 2 cells) and the secretions produced by these cells. Type 1 immune response is characterized by high phagocytic activity, whereas type 2 involves high levels of antibody production. Type 1 immunity is generally protective, whereas type 2 usually involves resolution of cell-mediated immunity. For more information, see Spellberg and Edwards (2001).

TABLE 1E10

Cattle breeds recorded in DAD-IS as showing resistance or tolerance to leukosis

Region/subregion	Number of breeds	Most common name of breed
Central Asia	1	Bestuzhevskaya
Europe and the Caucasus	9	Istobenskaya, Krasnaya gorbatovskaya, Southern beef, Suksunskaya skot, Sura de stepa, Yakutskii Skot, Yaroslavskaya, Yurinskaya, Volinian beef

Source: DAD-IS accessed in March 2014.

Bovine tuberculosis

Bovine tuberculosis is a respiratory disease that can be transmitted through milk and has significant negative consequences – both as a disease of livestock and as a zoonosis – particularly in developing countries. Several breeds (13 cattle breeds, 3 goat breeds and 1 sheep breed) are recorded in DAD-IS as being resistant to this disease. These breeds are primarily reported by countries from the Europe and the Caucasus region. Although it has not been recorded in DAD-IS, a recent scientific study (Vordermeier *et al.,* 2012) comparing native Zebu cattle to Holstein cattle in Ethiopia found that the Zebu was more resistant to tuberculosis. Within-breed quantitative genetic studies have found evidence of heritable control of susceptibility to this disease (e.g. Bermingham *et al.*, 2009; Brotherstone *et al.*, 2010; Tsairidou *et al.,* 2014) and genome-wide association studies have identified genomic regions with putative associations with disease incidence (e.g. Bermingham *et al.*, 2014).

Brucellosis

Brucellosis is a zoonosis that particularly affects cattle and goats. Transmission to humans is usually through consumption of contaminated milk or dairy products. Reproductive failure is the main negative consequence in livestock. Anecdotal claims of brucellosis resistance have been made in DAD-IS for one buffalo breed, seven cattle breeds, three goat breeds and two sheep breeds. Genetic studies have primarily concentrated on pathogen strains rather than livestock breeds, but a recent study of polymorphism in genes associated with immune function reported some associations with disease prevalence in cattle (Prakash *et al.*, 2014). In addition, Martínez *et al.* (2010) studied brucellosis resistance in two Colombian cattle breeds (Blanco Orejinegro and Zebu) and their crosses and observed statistically significant genetic effects according to both quantitative and molecular genetic models.

Scrapie

Scrapie is a fatal neurodegenerative disease of sheep and goats that is endemic in many countries in Europe and North America. Although no information on scrapie has been entered into DAD-IS, the disease can be considered a textbook case with regard to within- and between-breed genetic variability in disease resistance. It has been shown that variability of the so-called PrP locus accounts for a large proportion of the variation in resistance to the disease (Bishop and Morris, 2007). Selection for scrapie resistance based on PrP genotype has been implemented in various sheep breeds (Palhière *et al.,* 2008), including some at-risk breeds (Windig *et al.,* 2007; Sartore *et al.,* 2013). This has led to significant decreases in the frequency of one susceptible haplotype (VRQ), if not its elimination, and to increases in the frequency of a resistance haplotype (ARR). In many cases, it has been possible to implement efficient selection programmes to reduce the susceptible haplotype without having much effect on neutral diversity (Windig *et al.,* 2007; Palhière *et al.,* 2008). However, Sartore *et al.* (2013) reported an increase in inbreeding in the Italian Sambucana breed after selection started.

These contrasting empirical results underline the importance of considering genetic variability when designing selection programmes (Dawson *et al.,* 2008).

Foot rot

Foot rot caused by *Dichelobacter nodosus* or *Fusobacterium* is a highly contagious disease of sheep, in particular, and can cause production losses and animal welfare concerns. Table 1E11 shows breeds recorded in DAD-IS as being resistant to foot-rot infection. Current knowledge with regard to resistant breeds is similar to that available at the time the first SoW-AnGR was prepared. Disease control may in fact be better achieved through within-breed foot-rot lesion scoring (Conington *et al.*, 2008) than through breed selection. A recent epidemiological modelling study suggests that foot rot may be eradicated from a given flock by employing a combination of genetic selection, pasture rotation and timely antibiotic administration (Russell *et al.*, 2013; McRae *et al.*, 2014).

African swine fever

African swine fever is a highly contagious disease that causes the rapid death of infected animals. Although recent advances have been made in vaccine development, no commercial product is available and control still relies on strict protocols for disease identification, restriction of animal movements and culling of infected animals. The first SoW-AnGR highlighted the resistance of wild pigs to African swine fever.[5] DAD-IS now lists six breeds that are anecdotally reported to have some degree of resistance or tolerance to this disease, including breeds from Southern Africa, Spain and Jamaica. However, no scientifically confirmed reports of genetic resistance are available. Researchers in the United Kingdom have recently used gene-editing procedures to create domestic pigs with the putative genetic mechanism for resistance found in wild pigs (Lillico *et al.*, 2013).

Porcine reproductive and respiratory syndrome

Porcine reproductive and respiratory syndrome, more commonly known by the acronym PRRS, is a viral disease caused by the *Arteriviridae* family. The clinical signs of infection are manifold and can include widespread reproductive failure, including stillbirths, mummified foetuses, premature births and weak piglets. The disease also causes a characteristic thumping respiratory pattern in post-weaning piglets, which can lead to decreased growth and increased mortality. Containment and eradication of the disease is difficult due to the ease with which it is spread. No breeds are recorded in DAD-IS as being resistant to this disease, but differences between breeds and populations have been reported in the scientific literature (Lewis *et al.,*

[5] FAO, 2007, Box 14 (page 109).

TABLE 1E11

Breeds recorded in DAD-IS as showing resistance or tolerance to foot rot

Species	Region/subregion	Number of breeds	Most common name of breed
Cattle	Europe and the Caucasus	1	Sayaguesa
Sheep	North and West Africa	1	Beni Ahsen
	East Asia	1	Small Tailed Han
	Europe and the Caucasus	10	Bündner Oberländerschaf, Churra Lebrijana, Engadiner Schaf, Latxa, Leine, Montafoner Steinschaf, Owca kamieniecka, Polska owca długowełnista, Soay, Waldschaf,
	Southwest Pacific	1	Broomfield Corriedale

Source: DAD-IS accessed in March 2014.

2007). Reiner *et al.* (2010) report evidence of resistance to the virus in a population of "Wiesenauer Miniature" pigs developed in Germany; compared to animals belonging to the commercial Pietrain breed, the miniature pigs showed a 96.7 percent lower viral load. Research into the molecular explanation of resistance would allow for better understanding of the mechanisms of resistance to this viral pathogen. Such research is ongoing in a number of laboratories across the world (e.g. Lewis *et al.,* 2009; Boddicker *et al.,* 2012; 2014a,b; Serão *et al.,* 2014).

Diseases of poultry

Table 1E12 lists the avian breeds that are recorded in DAD-IS as being resistant to specific diseases Some level of general or unspecified resistance is reported for 75 other avian breeds (56 chicken, 11 duck, 2 goose, 3 guinea fowl, 1 pigeon, 1 quail and 3 turkey breeds).

Newcastle disease is a highly destructive viral infection affecting poultry and other avian species. The virus is endemic in certain areas of the world and can cause high levels of morbidity and mortality, particularly in intensive poultry management systems. A study comparing the relative resistance of three phenotypes of indigenous chickens in Nigeria found that Naked Neck chickens were more resistant to infection than others and more able to tolerate infection once it occurred (Bobbo *et al.*, 2013). The Yoruba chicken of Nigeria has been noted to have increased immune response to the virus and to be better able to resist and eliminate infection (Adeyemo *et al.*, 2012).

Over the last decade or so, avian influenza virus has become a global threat due to its devastating effects on poultry populations and the risks it poses to human health. No breeds are recorded in DAD-IS as being resistant to avian influenza. However, research indicates that the Mx gene in the Indonesian native chicken may confer increased resistance to infection (Sartika *et al.*, 2011). Moreover, resistance to the virus has been noted in the Fayoumi chicken breed, originally from Egypt but now present worldwide. Molecular analysis suggests that, in the event of infection, genes related to haemoglobin are highly expressed in the Fayoumi. Wang *et al.* (2014) postulate that this may aid the delivery of oxygen to various tissues, thus reducing the severity and duration of infection. Certain breeds of pigeons are known for their resistance to highly pathogenic avian influenza virus H5N1 (Liu *et al.*, 2009). Transmission of avian influenza in chickens relies in large part on specific receptors in the respiratory tract that allow the virus to attach. Analysis of these receptors in pigeons suggests that they are more similar to those of humans than those of chickens. Given that humans are also less susceptible than chickens to avian influenza H5N1, this could explain the pigeons' relatively high levels of resistance.

Genetic resistance to avian leucosis is recorded in DAD-IS for two Egyptian chicken breeds. Development of genetically resistant lines and the use of specific animal husbandry methods have enabled successful eradication of this disease from most commercial breeding populations.

4.3 Opportunities to breed for disease resistance

Breed-to-breed differences in disease susceptibility provide opportunities to decrease disease incidence through cross-breeding or breed substitution. However, these approaches are not applicable if the objective is to continue raising a given breed in pure-bred form or if relevant breed substitutions or cross-breeding strategies are not feasible. Therefore, for a number of diseases, selection to take advantage of within-breed variation in disease resistance is an important control strategy.

Numerous examples of within-breed selection for disease resistance exist and various selection strategies have been applied. Within-breed selection has been performed using both major genes and genetic markers (e.g. against scrapie in sheep) and quantitative genetic approaches (e.g. against Marek's disease in chickens, internal parasites in sheep and mastitis in dairy cows and sheep).

Within-breed selection programmes have always given emphasis to yield traits. However, consideration of heath traits has been increasing. This

TABLE 1E12
Avian breeds recorded in DAD-IS as showing resistance to diseases

Species	Region/subregion	Disease	Number of breeds	Most common name of breed
Chickens	North and West Africa	Newcastle	1	Poule De Benna
	Southeast Asia	Newcastle	1	Red Jungle Fowl
	Central America	Newcastle	2	Gallina criolla o de rancho, Gallina de cuello desnudo
	Europe and the Caucasus	Marek's	5	Scots Dumpy, Hrvatica, Borky 117, Poltavian Clay, Rhode Island Red
	Southeast Asia	Marek's, IBD (infectious bursal disease), coccidiosis	1	Ayam Kampong
	Southern Africa	Internal parasites	1	Basotho chicken
	Southeast Asia	Internal parasites	1	Papua New Guinea Native
		Respiratory diseases	3	Camarines, Paraoakan, Banaba (also fowl pox)
	North and West Africa	Mycoplasmosis avian pseudo plaque and pasteurellosis	1	Naked Neck
	Near and Middle East	Leukosis and spiroketosis	2	Egypt Baladi Beheri, Fayoumi
		Fowl pox and chronic respiratory disease (CRD)	1	Oman Baladi
	Europe and the Caucasus	*Eimeria necatrix*	1	Penedesenca Negra
		Oncorna virus	1	Single Comb White Leghorn-Line 12
Ducks	North and West Africa	Newcastle	3	Local Duck of Gredaya and Massakory, Local Duck of Moulkou and Bongor, Local Muscovy Duck of Karal and Massakory
	Southeast Asia	Duck viral enteritis and leg paralysis	1	Philippine Mallard Duck (Domestic)
	East Asia	Duck and goose viral hepatitis	1	Black Muscovy I303
Geese	Southeast Asia	Viral hepatitis	1	Itik Kampong
		"Skin venom"	1	Philippine Domestic Goose
Guinea fowl	North and West Africa	Newcastle	2	Djaoule, *Numida meleagris galeata* Pallas
Pigeons	Southeast Asia	"Skin venom"	1	Philippine Domestic Pigeon
Turkeys	North and West Africa	Newcastle	1	Moroccan Beldi
	Southeast Asia	Histomoniasis and sinusitis	1	Philippine Native

Source: DAD-IS accessed in March 2014.

has probably occurred for three main reasons: 1) greater awareness of the costs of disease; 2) decreasing fitness due to antagonistic relationships with selection and management for increased yield; and 3) increasing capacity to measure and evaluate health-related traits. In some cases, problems with other approaches, including the effects of increased resistance of pathogens to chemical and antibiotic treatments, have led breeders and livestock keepers to seek alternatives.

The most common approach to within-breed selection for health is not based on direct measures of resistance to a given pathogen, but rather aims to improve various phenotypes associated with disease complexes. For example, breeding for decreased mastitis may involve giving consideration to observed mastitis incidence, concentration of somatic cells (leukocytes) in milk and udder conformation. Selection against foot rot may be based on animal-mobility scores. Longevity is often included in selection indices as a measure of general health and disease resistance.

Some researchers have speculated that "–omics" technologies will greatly increase the capacity of breeders to incorporate genetic selection into disease-reduction programmes (e.g. Berry *et al.,* 2011; Parker-Gaddis *et al.,* 2014). The term "–omics" refers to a group of fields of advanced study of biological systems. Examples of potential relevance for the genetics of adaptation and disease resistance include "genomics", the study of genes and chromosomes; "transcriptomics", the study of transcribed gene products; "proteomics", the study of proteins; and "metabolomics", the study of metabolism. Genomics, particularly "genome-enabled" or "genomic" selection (see Part 4 Section C), may be particularly applicable to diseases for which measurement is difficult or expensive.

In the case of internal parasites, selection for resistance is successfully implemented in Australia and New Zealand by using faecal egg count as the selection criterion. However, measuring faecal egg count requires specific skills and equipment, which may not be available everywhere. One simpler alternative is to make use of the FAMACHA scoring system (a method of identifying anaemic animals by evaluating the redness of mucous membranes around the eyes) (van Wyk and Bath, 2002) to determine which animals within a small-ruminant flock are more resistant to parasites and should therefore be selected for breeding (Burke and Miller, 2008). A recent study reported low to moderate heritabilities of FAMACHA scores, indicating the possibility of using them as a selection criterion (Riley and Van Vyk, 2009). FAMACHA scoring is, however, only applicable in situations where *Haemonchus contortus* is the predominant parasite. The parasites more commonly found in temperate environments generally do not provoke anaemia and hence do not affect the colour of eye mucous membranes.

Research into genetic markers of within-breed resistance to internal parasites in Uruguay and other countries suggests that there are various molecular markers associated with resistance that could be used in selection programmes (e.g. Ciappesoni *et al.*, 2011). However, few of the associations observed for individual genes show consistency across breeds, presumably due to the biological complexity of parasite infection and the immune system (resulting in a polygenic nature for parasite resistance), as well as effects of recombination that cause differences among breeds in the linkage between genes affecting resistance and the genetic markers used in the research studies (Kemper *et al.,* 2011). In theory, genomic selection may be an effective means of controlling parasite infection (see Riggio *et al.,* 2014). However, the cost and expertise required mean that this approach is beyond the means of most sheep-breeding systems, particularly those in developing countries.

5 Conclusions and research priorities

The information recorded in DAD-IS, while incomplete, provides some indication of the state of knowledge of adaptive characteristics in breeds of livestock. In many cases, the information reported is anecdotal and has not been evaluated by scientific studies. More information is recorded for cattle and small ruminants than for other species. For some species that undoubtedly have specific adaptations (e.g. the yak), no information on breed-level adaptedness is recorded in DAD-IS. There is need for further research, particularly on species and breeds adapted to low-input production systems in developing countries or to other production systems where environmental conditions are harsh. Anecdotal information such as that provided in DAD-IS may, however, assist researchers in the identification of AnGR that merit further investigation of their adaptive characteristics.

Evidence indicates that, where the production environment is harsh, breeds whose evolutionary roots lie in the local area tend to be better adapted than breeds introduced from elsewhere. Thus, plans to introduce breeds into a new area must give due attention to ensuring that they are sufficiently well-matched to local conditions (taking into account temporal variations and the potential for extreme events such as droughts) and that any adaptations to livestock management practices that may be needed are feasible and sustainable. There is a need to set selection goals that are appropriate to the production system rather than ambitious performance objectives that cannot be reached under prevailing conditions. The integration of fitness traits into breeding programmes is constrained by a number of factors, including low heritability, measurement problems and underlying antagonistic relationships with productive performance traits. Research priorities include improving understanding of the functional genetics and genomics of adaptation traits and the identification and measurement of indicator traits of adaptation, with a view to their possible incorporation into breeding goals. Better mapping of breeds' geographical distributions and better description of their production environments (see Part 4 Section A) would facilitate the identification of breeds that are likely to be adapted to particular combinations of stressors.

Although the optimal approach will vary from case to case, the inclusion of genetic elements in disease-control strategies is often a prudent and effective approach. Documented successes have been achieved, but the use of genetics in disease control is still far from having reached its full potential, and continued research into the genetics of resistance and tolerance is needed. If breeds become extinct or within-breed diversity is lost before critical knowledge is gained and utilization strategies are developed, opportunities that could greatly contribute to improving animal health and productivity may be lost forever. Where the design and implementation of breeding programmes are concerned, consideration should be given to incorporating productivity and disease resistance as primary traits weighted according to their respective economic values.

Lack of information is the major constraint with respect to fully understanding the genetic mechanisms of disease resistance and tolerance in livestock. As noted throughout this section, many reports of breed-specific disease resistance are anecdotal, especially in developing countries, and are based on observations in a single production environment. Addressing the following research priorities would help to bridge these knowledge gaps and enhance the utilization of genetics in the control of animal diseases:

- continued phenotypic characterization to confirm anecdotal observations recorded in DAD-IS and elsewhere;
- genetic characterization to help understand the biological mechanisms underlying observed disease-resistance traits; and
- development of simple, accurate and cost-effective approaches for routine collection of phenotypic information on disease incidence, to support both characterization and genetic improvement.

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