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Key traits for ruminant livestock across diverse production systems in the context of climate change: perspectives from a global platform of research farms

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Abstract. Ruminant livestock are raised under diverse cultural and environmental production systems around the globe. Ruminant livestock can play a critical role in food security by supplying high-quality, nutrient-dense food with little or no competition for arable land while simultaneously improving soil health through vital returns of organic matter. However, in the context of climate change and limited land resources, the role of ruminant-based systems is uncertain because of their reputed low efficiency of feed conversion (kilogram of feed required per kilogram of product) and the production of methane as a by-product of enteric fermentation. A growing human population will demand more animal protein, which will put greater pressure on the Earth’s planetary boundaries and contribute further to climate change. Therefore, livestock production globally faces the dual challenges of mitigating emissions and adapting to a changing climate. This requires research-led animal and plant breeding and feeding strategies to optimise ruminant systems. This study collated information from a global network of research farms reflecting a variety of ruminant production systems in diverse regions of the globe. Using this information, key changes in the genetic and nutritional approaches relevant to each system were drawn that, if implemented, would help shape more sustainable future ruminant livestock systems.

Keywords: breeding goals, feeding strategies, genetic resources, global warming, grazing ruminants, sustainable intensification.

Introduction

Ruminant livestock are raised within diverse cultural and environmental production systems around the globe, where they play a critical role in global food and nutrition security while contributing to soil nutrient recycling via excreta. Such systems are recognised as an important part of an agroecological approach to sustainable production, driven by enhancing and maintaining soil health (i.e. soil organic C stocks, diverse populations of soil microbes, greater C sequestration; Teague *et al.* 2016; Chen *et al.* 2019). Ruminal livestock are intertwined within the livelihoods of many of the world's poor, providing nutrient-dense food and draught power, fuel, fibre, economic safety and social standing (Eisler *et al.* 2014; Gaughan *et al.* 2019). Moreover, animal-based foods are needed to secure adequate nutrition at the lowest cost (Chungchunlam *et al.* 2020). However, with regard to climate change, ruminant-based systems face an increasingly uncertain future, primarily because of the ruminant's unique digestive system that, while allowing the animal to use low-quality, fibre-rich feed (forage and by-products), produces the potent, if short-lived, greenhouse gas (GHG) methane as a by-product of anaerobic fermentation. In addition, increasingly variable and unpredictable environmental conditions mean that animal production will face numerous challenges, such as increased disease risk and increased nutritional deficiencies (Gaughan *et al.* 2019).

Globally, GHG emissions from livestock represent 14.5% (7.1 Gt CO_2eq annum^{-1}) of total anthropogenic emissions, whereas enteric fermentation from ruminants accounts for 39% of sector emission (Gerber *et al.* 2013). Climate change represents a significant threat to global food security and sustainable development for a growing global population, with a predicted increase of average global temperature at the end of the 21st century (compared with 1986–2005) between 1.0°C (Representative Concentration Pathway (RCP) 2 scenario) and 3.7°C (RCP8.5 scenario), with sustained interannual-to-decadal variability (Intergovernmental Panel on Climate Change (IPCC) 2013). This outcome will have both direct and indirect effects on livestock farming systems, as well as on human and animal health (Marino *et al.* 2016). Therefore, sustaining livestock production in a changing climate while reducing its environmental impact so as to not exacerbate the problem is the top priority for the agriculture sector (Gaughan *et al.* 2019).

At the same time, the growing, increasingly affluent human population will demand more animal-derived dietary protein, putting greater pressure on Earth's planetary boundaries (Steffen *et al.* 2015) and contributing further to climate change. It is therefore imperative that food is produced with fewer resources per unit product (i.e. 'impact intensity'), decreasing its effect on the environment. And even the operational definition of 'impact intensity' (units for numerator and denominator) can lead to the drawing of different conclusions when comparing different livestock systems (McAuliffe *et al.* 2018*a*). For example, crop food chains produce large amounts of residues and co- and by-products (non-edible foods), which constitute 32% of global livestock feed intake, whereas human-edible feeds (mainly grains) represent 14% of livestock diet (Mottet *et al.* 2017). Typically, ruminant grazing systems consume 0.2 kg human-edible feed protein per kilogram of protein product (0.6 kg kg^{-1} across all ruminant systems), whereas industrial monogastric systems range from 2.9 to 5.2 kg kg^{-1}. Therefore, when assessed using human-edible feed conversion, ruminants make a positive net contribution to the availability of human-edible protein. Moreover, 50% of the current global agricultural land used for livestock feed production is unsuitable for crops, and these lands are used entirely for grasslands to graze ruminants (Mottet *et al.* 2017). Therefore, for ruminant livestock to play a significant role in future sustainable food systems that incorporate optimal land use and reduced emissions, multidisciplinary approaches are required, including the integration of animal breeding, nutrition, housing and health to adapt and mitigate climate change (Gaughan *et al.* 2019).

In a position statement developed within the framework of an international network of instrumented research farms operating in contrasting production environments (https://globalfarmplatform.org, accessed 30 June 2020), Eisler *et al.* (2014) highlighted eight 'steps to sustainable livestock': (1) feed animals less human food; (2) raise regionally appropriate animals; (3) keep animals healthy; (4) adopt smart supplements; (5) eat quality not quantity; (6) tailor practices to local culture; (7) track costs and benefits; and (8) study best practice. A key point of emphasis was that in order to harness the benefits of ruminant livestock and reduce detrimental environmental effects, animals must be selected to suit their environment and available nutritional resources.

A systematic approach must be undertaken within the framework of a breeding program to ensure economic sustainability (Harris *et al.* 1984). For a given production system and the available genetic resources, a breeding goal is defined first (e.g. profit per cow, profit per hectare, kilogram of milk solids per 100 kg dry matter (DM) forage, kilogram of meat per hectare),

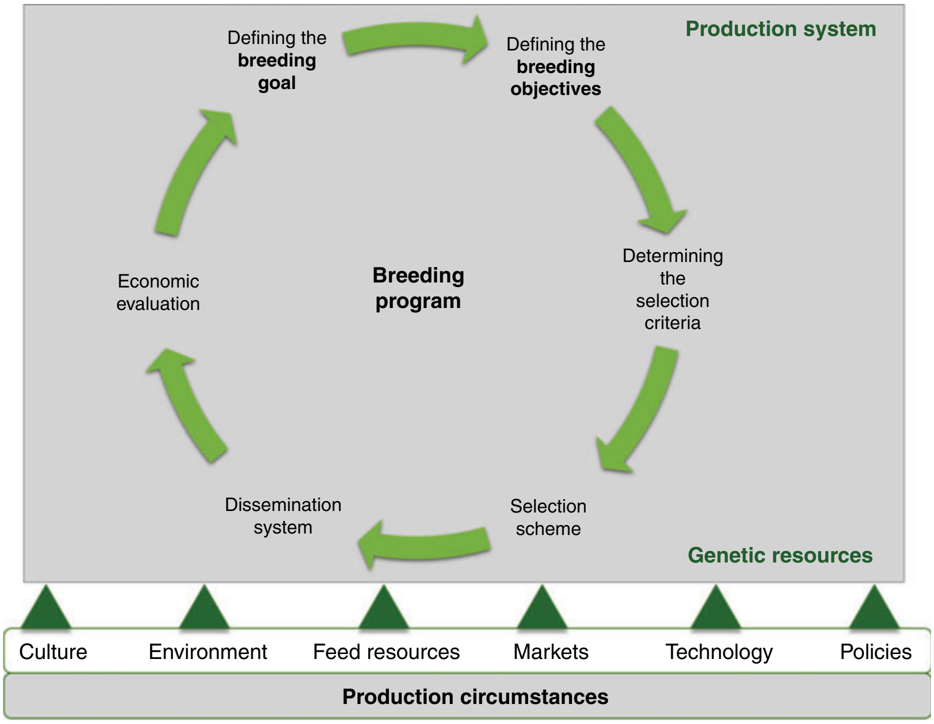

Fig. 1. Steps of a breeding program and its context: production system, genetic resources and production circumstances. (Adapted from Harris *et al.* (1984).)

followed by the definition of the breeding objective (i.e. the relevant traits and their relative economic weighting). These are the first steps of any sequential process to select the best animals for breeding future generations; the process must then be continually assessed for efficiency and adjusted to a new breeding goal when needed. This process is sensitive to the context of production because selection must be made to suit future production circumstances (Fig. 1). According to Groen (1989), production circumstances can be classified as 'natural' (e.g. climate, type of soil), 'social' (e.g. educational levels, traditions, statutory regulations) and 'economic' (e.g. market type, governmental policies, technological developments, price ratios). Under current and future global contexts, some of these circumstances may play more relevant roles in defining the breeding goals and objectives because climate change (environment), global markets and trends (economics) and acknowledgement of cultural diversity (social circumstances) are key drivers of current society. Currently, how the environment and resource availability differ across regions and how this affects local selection strategies has not been defined. Thus, the aim of this study was to identify and prioritise key traits relevant to a wide range of ruminant livestock systems across the globe, encompassing intensive and extensive production systems, as well as a range of climatic zones, under both current and future climate change conditions.

Materials and methods

The information collated in this study was obtained from 12 research farms (RFs) from around the globe, representing a variety of ruminant production systems and socioeconomic and geographical regions. A brief summary of the RFs is presented in Table 1 (additional descriptions are available in File S1, available as Supplementary Material to this paper).

The generation of information had three stages: preworkshop production, workshop discussion and post-workshop production. The workshop was hosted at Rothamsted Research, North Wyke, UK, in February 2020 and at least one representative of each RF attended (the representative of one RF attended virtually, and representatives of two RFs could not attend the workshop but participated in the other stages).

In the preworkshop stage, the RFs were asked to provide a list of livestock traits relevant to their RF under current climate conditions and a future climate change scenario (i.e. an increased global surface warming of 2°C by 2046–65; IPCC 2013). In addition, each RF was asked to provide a list of feeding strategies needed to reach the genetic potential for the livestock traits listed for each climate (current and future). The list of traits and feeding strategies was generated by each RF following different approaches (e.g. current selection indices in their countries, existing feeding strategies being tested at the RFs, discussion and analysis within the research team, existing guidelines or sector assessments, activities with stakeholders). A detailed description of the methods and drivers for defining the traits and feeding strategies is presented in File S2.

The 3-day workshop was split into key activities across the days, which involved working on other research outside this paper. The background and aims of this study were presented in a session on Day 1. In a second session on Day 2, an overview of the information submitted by each RF was presented and the

Table 1. Brief description of the research farms participating in the study (additional information is provided in File S1)

Dairy 1, Massey University; ESL, Embrapa South-east Livestock, Brazilian Agricultural Research Corporation; HRC, Henfaes Research Centre, Bangor University; INIA-PAP, National Institute of Agricultural Research – Palo a Pique research farm; INRAE-AM, Institut National de Recherche pour l'Agriculture, l'Alimentation et l'Environnement, Aster-Mirecourt research unit; INRAE-SLP, Institut National de Recherche pour l'Agriculture, l'Alimentation et l'Environnement – Saint Laurent de la Prée research unit; KRS, Kapiti Research Station, International Livestock Research Institute; NWFP: North Wyke Farm Platform, Rothamsted Research – North Wyke; SRUC-KA: Kirkton and Auchtertyre upland research farms, Scotland's Rural College; UCD-LTGP: Lyons Farm Long-term Grazing Platform, University College Dublin; UWA-FF: The University of Western Australia Future Farm 2050; UWP-PF: UW-Platteville Pioneer Farm, University of Wisconsin; LU, livestock unit

Farm platform	Location	Agroecosystem	Production system	Animals and breeds	Size and stocking rate	References
Dairy 1	Palmerston North, New Zealand	Temperate pasture	Grazing dairy, once-a-day milking	Dairy cattle, 75 Friesian, 56 Jersey and 119 Friesian × Jersey cross-bred	120 ha (effective)	Harrigan (2017)
ESL Dairy	Sao Carlos, Brazil	Subtropical humid pasture	Grazing and parlour feeding: dairy	Holstein, Holstein × Jersey	38 ha, 6.6 LU ha^{-1}	Berndt *et al.* (2014)
ESL Beef I	Sao Carlos, Brazil	Subtropical humid pasture	Intensive grazing (irrigated):beef	Nellore, Nellore × Angus, Senepol, Brangus, Brazilian Canchim	7 ha, 6.6 LU ha^{-1}	Oliveira *et al.* (2013)
ESL Beef II	Sao Carlos, Brazil	Subtropical humid pasture	Integrated crop–livestock–forest: beef	Nellore, Nellore × Angus, Senepol, Brangus, Brazilian Canchim	30 ha, 2.6 ha^{-1}	Bernardi *et al.* (2018)
HRC	Bangor, Wales, UK	Temperate: oceanic upland and lowland	Grazing: sheep	Welsh mountain	30 ha lowland, 70 ha upland, 2 LU ha^{-1}	Marsden *et al.* (2018)
INIA-PAP	Treinta y Tres, Uruguay	Temperate grassland	Crop–livestock rotations: beef	Hereford, Angus, Hereford × Angus	150 ha, 0.74–1.46 LU ha^{-1}	Rovira *et al.* (2020)
INRAE-AM	Mirecourt, France	Temperate: organic, agroecological approach	Grazing dairy	20 Holstein, 20 Montbeliarde	78 ha permanent grassland, 0.87 LU ha^{-1}	Coquil *et al.* (2009)
INRAE-SLP	Saint-Laurent-de-la-Prée, France	Atlantic wetland grassland: organic, agroecological approach	Crop–livestock: beef	55 cows, Maraîchine (dual-purpose breed: milk and meat)	160 ha (115 ha wetland permanent grassland), 0.7 LU ha^{-1}	Durant *et al.* (2020)
KRS	Nairobi, Kenya	Semi-arid rangeland	Livestock–wildlife: dairy, beef, sheep, goats and camels	2800 cattle (Boran, Boran × Frisian), 1500 sheep (Red Masai, Dorper × Red Masai), 500 goats, 70 camels	13 000 ha, 0.16 LU ha^{-1}	ILRI (2019)
NWFP	Okehampton, England, UK	Temperate lowland pasture	Grazing beef and sheep and intensive housed beef	30 cattle (Stabiliser) and 75 ewes (Suffolk mule) plus lambs (from Charolais rams) per farmlet (two farmlets), plus 30 cattle housed	22 ha × two farmlets, 2 LU ha^{-1}	Orr *et al.* (2016)
SRUC-KA	Crianlarich, Scotland, UK	Rangeland	Grazing sheep and beef	1400 ewes (~1150 Scottish blackface, 200 Lleyn, 50 hill-breed cross-bred), 27 cows (Angus)	2200 ha (~70 ha improved grassland, 150 ha semi-improved pastures, 1700 ha unimproved upland moorland grasslands), from 0.2 LU ha^{-1} to 0.5–1.0 LU ha^{-1}	https://www.ruralbrexit.scot/innovation-in-upland-livestock-systems-srucs-hill-mountain-research-centre/ (accessed 30 June 2020)
UCD-LTGP	Dublin, Ireland	Temperate pasture	Grazing dairy × beef	Dairy × beef calves (Hereford bull with dairy cows)	24 ha, 2.5 LU ha^{-1}	https://www.ucd.ie/lyonsfarm/research/long-termpasture-basedproductionsystemsresearch/ (accessed 30 June 2020)
UWA-FF	West Pingelly, WA, Australia	Drylands	Crop–livestock: sheep	3000 ewes (Merino)	1588 ha (1088 ha pasture)	www.ioa.uwa.edu.au/future-farm-2050 (accessed 30 June 2020)
UWP-PF housed, UWP-PF grazing	Platteville, WI, USA	Gently rolling fields	Free-stall dairy, crop–livestock dairy	170 Holstein cows (150 confined, 20 under management-intensive grazing)	178 ha (20 ha permanent pasture)	Stuntebeck *et al.* (2011)

options for analysing and processing the information collected were discussed and agreed. The discussion was moderated in order to allow all participants to express their views and arguments, and a consensus was achieved on the procedure for prioritising the different traits in both scenarios. The visualisation of the complex dataset was also agreed.

At the post-workshop stage, the relevance of each trait was represented by its priority for selection (i.e. low, medium and high). There was no lower or upper limit in the number of traits to be listed, and it was agreed that there was no predetermined proportion of the traits to be assigned to each priority category (e.g. all traits could have high priority).

The relative relevance of 10 categories of traits was calculated within each RF and for each animal category. Individual traits within each of the 10 categories were assigned a value of 1, 2 or 3 points for low, medium and high priorities respectively, regardless of the direction of the desired change (increase or decrease). The sum of points for each category was expressed as a percentage of the total points for each RF. The 10 categories defined were as follows: performance (e.g. milk production, milks solids production, growth rate, carcass weight and conformation, days to finishing, carcass fat and muscle, kill-out percentage); product quality (e.g. milk solids percentage, somatic cell scores, fatty acids profile, meat and carcass quality, wool quality); efficiency (e.g. cow and ewe mature liveweight, feed efficiency, feed intake, longevity); reproduction (e.g. fertility, reproduction efficiency, number or percentage of lambs reared); calving/lambing (e.g. birthweight, calving and lambing ease, unassisted calving and lambing, lambing time); maternal ability (e.g. maternal quality, calf mortality, milk production, weaning weight, kilogram of lamb weaned per kilogram of ewe); workability (e.g. docility, temperament, udder quality, milking speed, polled livestock); health (e.g. resistance to diseases, resistance to parasites, resistance to worms, wellness); adaptability (e.g. heat tolerance, adaptation to grazing, resilience, hardiness, versatility, wool shedding); and environment (e.g. GHG emissions, water use efficiency (WUE), efficiency of nitrogen use).

Results and discussion

Ruminants account for 49% of global protein production: (1) 33.5% is produced in grazing systems (i.e. where more than 90% of DM fed to animals comes from rangelands, pastures and annual forages and less than 10% of the total value of production comes from non-livestock farming activities); (2) 4% is produced in feedlots (this figure only accounts for beef, where cattle are mostly fed on purchased grain); and (3) 62.5% is produced in mixed systems (systems in which more than 10% of the DM fed to animals comes from crop by-products or stubble or where more than 10% of the total value of production comes from non-livestock farming activities; Mottet *et al.* 2017). Of the 15 research units participating in this study (Table 1), nine are pasture based, with or without strategic supplementation (grazing: Dairy 1, ESL-Beef I, ESL-Dairy, INRAE-AM, HRC, KRS, NWFP, SRUK-KA and UCD-LTGP; see Table 1 for details), five are part of a crop-livestock systems (mixed: ESL-Beef II, INIA-PAP, INRAE-SLP, UWA-FF and UWP-PF 'managed-intensive-grazing') and the remaining unit (UWP-PF confined) consists of a free-stall system where cows are fed total mixed rations. Therefore, the selection of RF may under-represent the mixed systems in favour of grazing systems, whereas the more intensive free-stall, high-yielding dairy systems seems to have little representation (no statistics were found regarding the share of global milk production over different system intensity levels). However, because the latter system is predominately driven by controlling the animal's environment (housed), it is less relevant to the present assessment. In addition, given the role livestock have in converting human non-edible protein into high-quality products, we put the emphasis on those systems that constitute the network of RFs (i.e. mixed and grazing).

The full lists of traits for each RF are presented in Files S3–S5 for dairy cattle, beef cattle and sheep respectively, along with an indication of the direction (intended increase or decrease) and priorities for selection. The main findings and trends are discussed below for each animal category.

Key livestock traits and their priority under current climates

Dairy systems

Of the dairy systems included, UWP-PF is the only RF that is running a confined intensive dairy system, which, in turn, is being compared with a managed intensive grazing system. For the UWP-PF variable forage-based diets, typical of managed intensive grazing, the trait associated with *milk yield consistency* is more important than under the confined systems with a consistent diet. Forage-based dairy systems are run by KRS in a semi-arid environment and by ESL in a subtropical humid environment. For all these farms, the trait *milk production* is relevant, although with different directions and strategies. The breeding objective of Dairy 1 is aligned to that of the New Zealand Dairy Industry, which is breeding cows for genetic superiority to convert feed (pasture and other supplementary forages with few concentrates (cereals)) into farm profit. The selection index put positive relative economic emphasis on *protein*, *fat*, *fertility*, *body condition score* and *survival*, and negative relative economic emphasis on *milk volume*, *liveweight* and *somatic cell score*. The relative economic emphasis reflects the needs of breeding a cow that: (1) produces milk to be processed into dairy products (milk powder predominately) for international markets (water must be evaporated); (2) calves annually in the spring; (3) is pregnant in early summer; and (4) has a low liveweight to be able to walk and facilitate grazing pasture for conversion into milk protein and fat. INRAE-AM aims to adapt *milk production* based on the resources available (exclusively permanent pastures), which may result in a decreased production to align with reduced dependence on inputs, and their costs, and would contribute to overcoming reproductive problems (by reducing the trade-offs between production and reproduction). Conversely, both ESL and KRS are interested in increasing *milk production* by crossing local adapted *Bos indicus* breeds (Boran) with highly productive *Bos taurus* breeds, namely the Holstein × Friesian in KRS and the Holstein × Jersey in ESL. At ESL, the entire production system is undergoing transformation to systems that are more environmentally resilient and favourable to animal welfare, through crop–livestock–forest integration (CLFi). *Milk composition*, linked to *milk volume*, is identified as an important trait for most RFs, although the focus varies from solids production to content. This decision is determined by the payment systems, the target market of the region or country, the seasonality of milk production or export potential.

Traits related to maintenances costs, such as *liveweight* (LW) and *frame size* (dairy cattle), are seen as relevant for Dairy 1 (high priority) and INRAE-AM (medium priority). The aim is to reduce costs as well as to produce animals that are better adapted to grazing conditions. In this regard, *feed conversion efficiency* from forage is particularly relevant for the RFs operating in warmer environments (ESL and KRS). Understandably, the traits related to *reproduction efficiency* are relevant for all dairy RFs, with medium to high priority. Particularly for UWP-PF, the confined system has a medium priority for this trait compared with the managed intensive grazing, where the trait has a high priority due to the milk production advantages of synchronising dairy cow lactation curve and pasture growth curve.

Other traits related with *calving ease*, *maternal quality*, *udder characteristics* and *milking speed* were also highlighted by some RFs. Health-related traits such as *heat tolerance* and *parasite resistance or tolerance* were highlighted by some RFs, assigning low and medium priorities; again, priorities differ between confined and managed intensive systems, with higher priorities in the grazing system. Environmental traits such as *GHG emissions* and *WUE* were also highlighted for UWP-PF and ESL, with low and medium priorities based on their research objectives and local constraints.

Beef systems

For beef cattle, *growth rate* is a high priority trait for selection at INIA-PAP, SRUC-KA and the NWFP, whereas for ESL the improvement in the traits is via cross-breeding. At ESL, they are using either the simple cross Nellore × Angus or composite beef breeds such as Senepol (five-eighths Red Polled, three-eighths N'Dama), Brangus (five-eighths Angus, three-eighths Brahman) or Brazilian Canchim (five-eighths Charolais, three-eighths Zebu) to improve *growth rate*, *carcass characteristics* and *disease and parasites resistance* on grazing systems. *Carcass quality* and *conformation* are a group of traits relevant for UCD-LTGP and NWFP that relate to market conditions (payment system). Conversely, INIA-PAP prioritises meat *eating quality*, particularly *tenderness*, because Uruguay exports 70–80% of the beef produced. However, this represents only 3.5–4.0% of the global exports share; therefore, Uruguay's strategy is to differentiate their product based on quality to be competitive in international high-value markets. For traits related to costs, such as *feed intake*, *feed efficiency* and *animal size*, all the RFs with beef cattle prioritise some of those traits. The aim is to reduce *feed intake* (high and medium priority for UCD-LTGP and NWFP respectively), whereas INIA-PAP highly prioritises animals with *low maintenance requirements* due to a reliance solely on on-farm feed. Similarly, SRUC-KA and NWFP give low *cow mature LW* medium priority (to reflect the poor grazing resource available on upland vegetation and the need to reduce GHG emissions on lowland vegetation respectively), whereas INIA-PAP puts the same emphasis on *moderate frame size* for animals. Cattle vary widely in body size, but optimal size depends on the production system and end market. The emphasis on selecting for growth rate has favoured leaner, faster-growing cattle, which, in turn, has led to an increase in the mature size of cattle that may not necessarily be advantageous (e.g. because of higher maintenance costs; Arango and Van Vleck 2002). At ESL, genetic selection for 31 years in the Brazilian Canchim breed has resulted in higher daily feed intake and higher daily LW gain, but with the same methane emissions per kilogram of animal LW than the non-selected line (Méo-Filho *et al.* 2020). Therefore, given the importance of body size in relation to efficiency, traits associated with size (mass and dimension) are being included in selection and cross-breeding programs (Arango and Van Vleck 2002). *Feed conversion* efficiency is a relevant trait for most of the RFs, particularly *feed efficiency on forage* diets such as grazing and on conserved forage (hay, silage), with medium and high priority respectively, for selecting more efficient converters of low-quality feed into meat. According to Basarab *et al.* (2013), selecting for feed efficiency through residual feed intake (RFI) or its component traits (DM intake, LW, mean daily gain and backfat) in a multitrait selection index will result in slow incremental improvement to feed efficiency and methane intensity, with few antagonistic effects on traits of economic importance.

As with dairy cattle, traits related to *reproduction efficiency*, *calving ease* and *maternal ability* are also relevant for beef cattle for the RFs. The *reproduction efficiency* and *fertility* of the cow are high-priority traits for five of the seven farms with beef cattle systems, with UCD-LTGP adding *gestation length* (with low priority) as an indicator of reproduction efficiency. All the farms except SRUC-KA (where the herd is relatively recently established, the herd size is small and few problems with reproductive traits have been experienced) are aiming to improve this indicator. After reproduction efficiency, calving is a key aspect for most of the RFs with a breeding herd: SRUC-KA and NWFP aim to reduce *birthweight*, KRS (because of the size of the farm and the availability of resources, such as veterinary support) and INRAE-SLP put high emphasis on *unassisted calving*, and UCD-LTGP puts a low priority on reducing *calving difficulty* and a high priority on decreasing *calf mortality*. Even though INIA-PAP has not included reproductive efficiency as a relevant priority trait for its system, given it only hosts growing and finishing beef cattle, it acknowledges its indirect effect securing the provision of calves each year. Given the negative association between birthweight and calving ease (Johanson and Berger 2003), prioritising birthweight in selection programs would increase calving ease and unassisted calving. There is some evidence that pelvis dimensions should be measured, because of their value in predicting dystocia (Johanson and Berger 2003). Similarly, *maternal ability* traits (*milk production*, *maternal quality*, *weaning weight*) are high-priority traits for most of the farms with a breeding herd. Interestingly, docility is considered a relevant trait for KRS, INRAE-SLP, UCD-LTGP and NWFP, albeit with priority varying (from low to high), perhaps reflecting the intensity of handling and labour within each system, and particularly because of the size of the herds (≥100 head managed by one herdsman) in ranching systems such as at KRS. In the case of INRAE-SLP, it has a traditional and rustic dual-purpose breed to the wetlands with horns and lively temper that can lead to injuries between animals and, very rarely, to farmers. By prioritising *docility*, INRAE-SLP is aiming to improve welfare for animals and farmers. The two most important components that determine the efficiency of beef cows are milk production (which will influence offspring growth and weaning weights) and mature bodyweight (Arango and Van Vleck 2002), so, as exemplified by the selections of the RFs, these traits should be emphasised in breeding programs to improve the efficiency of the cow–calf system.

Resistance to disease and parasites, as well as general *animal health*, are also relevant traits of high priority for selection for KRS, INIA-PAP and INRAE-SLP (the parasitic pressure is particularly high in marshland context), whereas ESL opts for cross-breeding with tropical-adapted breeds such as Nellore (*B. indicus*) or a composite breed, such as Senepol, Brangus or Brazilian Canchim, to incorporate *disease resistance* into the herd. In addition, *heat tolerance* was identified as a selection trait for KRS and INRAE-SLP, where conditions are more challenging, although at a lower priority than for other traits. A trait related to environmental impact, such as *WUE*, is only considered by ESL (medium priority), perhaps reflecting greater access to water, such as adoption of CLFi systems with irrigation, or to genotypes that are already water efficient (e.g. *B. indicus*), perhaps to the levels of performance expected at other RFs.

Sheep systems

For the RFs with small ruminants, performance traits such as *growth rate* (SRUC-KA and NWFP), *days to finish* (HRC) and *lamb kill-out percentage* (HRC) are of high priority, whereas *carcass weight* has medium priority for NWFP. Product quality traits are also prioritised for some RFs, such as SRUC-KA, which has low priority for *carcass quality* indicators, NWFP, which puts medium priority on achieving *premium carcass* class, and UWA-FF, which gives priority to *wool quality*, although at a lower level than for other traits. In UWA-FF, wool earns approximately one-third of the farm income, but to do so it must be high quality (fibre diameter 18 µm). Moreover, economic resilience depends on a diversity of products (i.e. markets) and wool is as important as meat and the grain crops, even though it does not fit the goal of food security (Eisler *et al.* 2014). For UWA-FF, *resistance to parasites* and flystrike are seen as critical because they are highly heritable yet cost Merino farmers in Australia at least A$500 million per annum and the current preventive measures, anthelmintic medications and mulesing, are at risk of disappearing, the latter reassuringly so in terms of animal welfare (Zhao *et al.* 2019). Traits related to efficiency of the systems, such as *feed conversion on pasture*, are a high priority for KRS, NWFP and UWA-FF, whereas *ewe mature LW* has medium priority for SRUC-KA, which reflects the low-input nature of the systems and the environmental challenge imposed on the ewe, especially in upland conditions.

Reproductive and *maternal ability* traits are of medium to high priority for all the RFs. *Reproduction* has high priority for KRS and UWA-FF, with the latter highlighting its effect in many aspects of system efficiency, including reduced intensity of methane emissions. This view is consistent with earlier studies showing fertility is a trait that has a large effect on system efficiency in livestock production: more fertile females, particularly those with good longevity, have more offspring, and so dilute their own feed requirements over this increased number of offspring (Hegarty and McEwan 2010; Hayes *et al.* 2013).

Key livestock traits and their priority in the climate change scenario

Dairy systems

Compared with the current climate, *milk production* and *milk composition* remained similar for the dairy systems, except for Dairy 1, which would consider decreasing the relevance of *milk production* (*less volume*). Research will continue at Dairy 1 on *fatty acids* (e.g. softer butter, omega-3 fatty acids) and opportunities to exploit variation individual *milk proteins*, such as the case of a2 Milk$^{\text{TM}}$ (The a2 Milk Company). For the confined system at UWP-PF, the relevance for *milk yield consistency* under variable feed quality would become more relevant (changed from low to medium priority) because of a potential change in nutritional composition of the forage (Lee *et al.* 2017) comprising the total mixed ration, whereas for the managed intensive grazing they would overcome this limitation through selection of plant species mixtures and/or alternative management methods. It is important to note that for INRAE-AM the future production system will no longer be a specialised dairy farming system, but a more complex system in which cattle are integrated, complementing sheep and pig production and crops for human consumption to limit feed-food competition.

Feed conversion efficiency of forage (either grazing or conserved) would become more relevant under a warmer environment, with its priority increased by ESL (from medium to high), and it will become a relevant trait for Dairy 1. The increase in efficiency of utilising feed resources could be a key factor to overcome potential reductions in feed availability and quality under climate change conditions. This highlights the relevance of estimating the correlation (genetic and phenotypic) between feed efficiencies estimated under confined controlled systems with energy-dense and consistent diets versus forage-based trials (on silage or grazing trials) either in single or CLFi systems. This may also result in a new approach where the estimated breeding values for feed efficiency are estimated under 'similar' conditions to the future production environment (forage based, warmer environments, under grazing). The challenge is to refine the technology or develop new technologies that can be used to more accurately estimate individual pasture intake by cattle (Arthur *et al.* 2004).

Fertility and *reproduction efficiency* are of high priority for all the RFs. Milk production in New Zealand will continue to be pasture based with a seasonal spring calving to keep the synchronisation of pasture growth with DM requirements of the herd. This requires that the high genetic superiority for fertility achieved by the New Zealand herd will be maintained or increased to ensure that more than 80% of the cows become pregnant in 8 weeks of AI during late spring and early summer. *Udder support*, *milking speed*, *udder capacity* and *front teat placement* as functional traits will remain important in the climate change scenario for Dairy 1. For the confined system at UWP-PF, the *fertility* trait is expected to increase its relevance under a warmer scenario because of reduced fertility due to heat stress in confined operations. In a scenario where issues with reproduction and calving occur, INRAE-AM would consider cross-breeding with hardy dairy breeds (Vosges, Jersey, Alpine Brown or Scandinavian Red) to overcome these problems.

For behavioural traits, *temperament* would start to be considered for INRAE-AM to improve farmers' working conditions and because INRAE-AM envisages an ecological intensification of the rearing of heifers under suckler herds. For KRS, the relevance of *docility* would decrease (from medium to low) as other traits become more relevant, in particular *heat tolerance* and *feed conversion efficiency*. *Calving ease* would become relevant for INRAE-AM with the aim of improving the working conditions of farmers.

Health-related traits, namely *parasite resistance and tolerance*, remain relevant for the same RFs in the future scenario and even gain relevance for both UWP-PF systems; ESL would start considering the *resistance to parasites, blood-borne diseases and ticks* in a warmer environment. The rising priorities of these traits would be expected to counterbalance expected increases in the incidence of parasitic infections in warmer conditions caused by an expected greater abundance and changes in geographical distribution (Morgan and Wall 2009). Similarly, *heat tolerance* would become a more relevant trait for KRS (from medium to high priority) and would be part of the selection process in Dairy 1. This trait has a heritability of between 0.17 and 0.23 for Holstein and 0.18 to 0.27 for Jersey (Nguyen *et al.* 2016), varying with the trait being affected by the heat stress (milk yield, fat yield, protein yield) and parity (first calving or calving 1–3). The moderate heritability values show that this trait could be improved by selection but, in a multitrait selection index, correlations with other production and functional traits will need to be considered to ensure a balanced outcome (Nguyen *et al.* 2016). The breeding program of Dairy 1 would also start including *resilience*, the capacity of an animal to be minimally affected by disturbances or to rapidly return to a predisturbance state (Berghof *et al.* 2019). However, indicators for general resilience to environmental disturbances have not been defined, and perhaps are therefore not yet being included in breeding objectives of livestock (Berghof *et al.* 2019). Adaptability traits would also be relevant for some RFs: Dairy 1 would give *adaptation to once-a-day-milking* a high priority to reduce labour without compromising profitability (milk solids for export) and improve farmers' well-being and animal welfare (less distance walked, less lameness and less energy expenditure in activity), whereas INRAE-AM would keep the medium priority for *adaptation to grazing* under their once-a-day milking system. Berghof *et al.* (2019) demonstrated that including resilience in breeding programs has great potential for producing healthy and easy-to-manage livestock, with resilience indicators based on deviations between observed and expected production. Berghof *et al.* (2019) also concluded that an economic value for resilience indicators in the selection index can be determined based on reductions in labour costs and health costs. Therefore, more data are required before this trait can be formally included in breeding objectives (Berghof *et al.* 2019).

Environment-related traits would be more emphasised in the context of climate change because *GHG emissions* or *WUE* would increase their relative importance for all RFs, and many current selection indices do not include these traits. For example, there is evidence that under subtropical conditions (ELS dairy system) cross-bred Jersey × Holstein cows emit less methane (g CH_4 day^{-1} and g CH_4 kg^{-1} produced milk) than purebred Holstein, whereas milk yield per hectare or per cow is comparable (Berndt *et al.* 2014). The challenge with these types of traits is estimating their economic value so they can be assigned a relative weight within the breeding objective. Bell *et al.* (2017) proposed to calculate the economic value of enteric methane by calculating the extra feed required for energy lost as methane for herd replacements, lactation and energy lost due to the heat increment from fermentation. These authors found that enteric methane emission has less economic importance, when measured only on an energy-based approach, for herd profitability than animal survival, milk production traits (composition and volume), calving interval and feed intake. Moreover, Bell *et al.* (2017) suggested that improvements in correlated traits, such as feed efficiency, may be more cost-effective in reducing emissions given the difficulty of measuring such phenotypes compared with existing traits recorded for milk production, health and fertility. However, this relative economic importance may change if possible future costs of GHG emission (e.g. carbon taxes) are included in the models to derive economic values of the traits in the breeding objective. Therefore, policy-driven demands for reductions in methane and other pollutants may provide further economic value (by avoiding fines, reducing taxes or producing carbon credits) for greater selection of environment-related traits in the future. Because the emission of methane can be reduced but not avoided, there is an opportunity to explore carbon removal strategies in livestock production systems, mainly through the accumulation of carbon in soils and biomass, especially within in CLFi systems.

Even though all the traits proposed by the RFs are relevant and would be included in a selection process, there are relative changes that differ among farms. The overall trend in changes between current and future climate for the categories of traits defined for dairy cattle is shown in Fig. 2 and File S6. *Environment*, *adaptability* and *health*-related traits were the categories that would increase in relevance in a climate chance scenario at expense (lesser emphasis) of, in general, *performance*, product *quality* and *efficiency*. In particular, ESL increased *health*-related traits by 37.5% (compared with their relevance in the current climate) due to the increased relevance of resistance to parasites, even at the expense of *adaptability* and *reproduction* traits. This difference in relative relevance of the traits could be driven by the warm and humid climate where these farms operate. Conversely, Dairy 1, operating in a temperate climate, would increase the *environmental* and *adaptability* traits by 13% and 20.5% respectively at the expense of *workability* and *performance*, given the national policy of reducing GHG emissions and reducing labour inputs, as well as improving the nutritional value of food. A different profile is shown by INRAE-AM, where the main driver for their changes is the need to improve *fertility* and to reduce *reproduction* and *calving* problems. INRAE-AM is also driven by the need to improve work conditions for farmers and the need to raise animals adapted to grazing systems; therefore, they would increase the relative relevance of *workability*, *efficiency* and *adaptability*

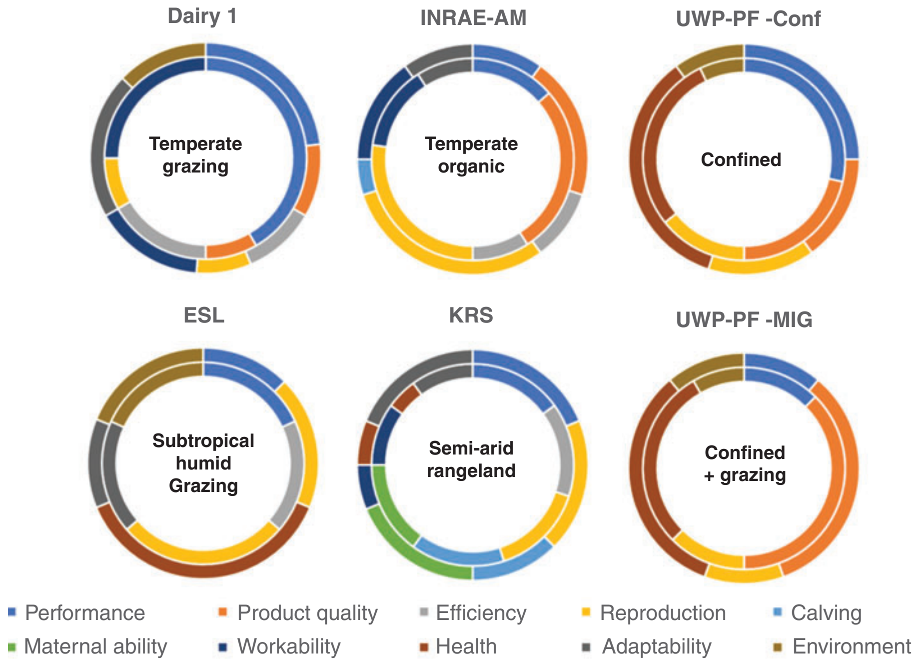

Fig. 2. Relative relevance for selection of traits categories in dairy cattle within the different research farms in the current climate (inner circle) and in a future climate change scenario (outer circle; increased global surface warming of 2°C by 2046–65). Individual traits within each of the 10 categories were ranked as low, medium and high priority, and assigned 1, 2 or 3 points respectively. The sum of points for each category was expressed as a percentage of the total points for each research farm. Dairy 1, Massey University; ESL, Embrapa South-east Livestock, Brazilian Agricultural Research Corporation; INRAE-AM, Institut National de Recherche pour l'Agriculture, l'Alimentation et l'Environnement, Aster-Mirecourt research unit; KRS, Kapiti Research Station, International Livestock Research Institute; UWP-PF: UW-Platteville Pioneer Farm, University of Wisconsin; Conf, confined; MIG, management intensive grazing.

traits, although to a lesser extent than *reproduction* and *calving* traits. All these relative increases would be at the expense of reducing the relative importance of *performance* and product *quality*.

Beef systems

For beef cattle, performance traits would maintain their priority compared with the current climate, except at NWFP, which would slightly decrease the relevance of these traits. Even for the climate change scenario, the goals of the cross-breeding program for beef cattle of ESL is focused on *growth rate* associated with *meat quality* of animals reared under intensive grazing systems and finished either on pasture or in confinement. *Meat quality* would still be a priority for NWFP and INIA-PAP in a future climate change scenario as a means of improving the provision of nutrients for humans with more efficient animals, as consumer preference in advanced economies will likely shift towards the consumption of smaller amounts of livestock products, driven by environmental concerns, of higher nutritional or welfare quality (McAuliffe *et al.* 2020). Even though *feed intake per se* would no longer be considered a main priority, *frame size* and *cow mature weight*, as proxies of maintenance costs, would increase in priority for INRAE-SLP and NWFP. This highlights the role animal size may play in a climate change scenario because it is related to both maintenance requirements and adaptation to warmer conditions (Elayadeth-Meethal *et al.* 2018). *Feed efficiency*, particularly of forage-based diets, would gain relevance in the future scenario, highlighting the importance of improving the use of home-grown feed resources that would likely be accompanied by variations in nutritional value (Howden *et al.* 2008).

All the RFs would maintain the *reproduction*-related traits as a high priority. However, the priority of traits related to calving ease (*birthweight*, *unassisted calving*, *calving difficulty*) would decrease for some RFs (KRS, NWFP), whereas *maternal quality* traits would generally remain as a priority in a climate change scenario. For behavioural traits, such as *docility*, there would be a reduction in priority for KRS and they would no longer be key selection traits for NWFP, whereas UCD-LTGP would start selecting animals that were *easier to manage* (low priority) encompassing aspects such as docility and less requirement for handling.

As with dairy cattle, traits related to *animal health* in beef cattle would become more relevant under the climate change scenario than in the current climate for all RFs except SRUC-KA, which would, nevertheless, start selecting beef cattle based on *hardiness* to cope with predictions of more variable rangeland and upland conditions. Coincidently, hardiness is one of the main criteria when selecting breeds for rangeland environments, along with longevity and fertility (Morgan-Davies *et al.* 2014).

Similarly, ESL would improve *disease and parasite tolerance* by using adapted breeds (Oliveira *et al.* 2013) and resilient production systems, such as the silvopastoral approach (De S. Oliveira *et al.* 2017). Selection for *resilience* would start being highly prioritised by INIA-PAP and UCD-LTGP to develop cattle that are more able to cope with and thrive during extreme external perturbations. It is no surprise that for many of the RFs *heat tolerance* is the adaptation trait that would become more relevant in a warmer environment, achieved either by selecting for the trait or by cross-breeding with native breeds that are better adapted to harsh conditions. According to the study of the Angus breed by Bradford *et al.* (2016), direct heritability for heat tolerance is 0.24 for weaning weight and 0.32 for yearling weight, with values for heritability decreasing as heat load increases, as is also the case for maternal heritability. Despite the slightly lower direct heritability for heat stress tolerance for weaning weight, this trait presents phenotypic plasticity, indicating potential for users of Angus genetics in extreme environments to make greater genetic improvement by using environment-specific genetic predictions (Bradford *et al.* 2016). All RFs (ESL, UCD-LTGP, SRUC-KA, NWFP) expect an increase in priority for traits with an environmental impact, such as *WUE* and *GHG emission*. As discussed by Hegarty and McEwan (2010), possible objectives include: a reduction in total emissions from the sector, farm or individual animal; a reduction in emissions intensity (emissions per unit animal product or profit); or reductions in methane yield (g kg^{-1} feed) to not only reduce environmental cost but also to likely align with policy requirements (intervention). Cottle and Van Der Werf (2017) tested the approach of harnessing the high correlation (0.67–0.82; Basarab *et al.* 2013) between daily methane production (DMP) and daily (pasture) feed intake (DFI), acknowledging that both are difficult and expensive to measure in pasture-based systems, so only a few animals could be measured. Cottle and Van Der Werf (2017) found that the selection response for DMP only became negative when at least 40% of males had DFI estimates, although the optimum number of males to measure depends on breeders' attitudes towards return of investment and the value of genetic change for DMP. Reductions in DMP can be achieved through genetic selection of more feed-efficient beef cattle with low RFI intake, reducing not only emissions, but also feed costs without compromising growth rate (McAuliffe *et al.* 2018*b*). An Australian study demonstrated that the annual methane abatement in Year 25 of selection would be 15.9% lower than in Year 1 for an individual adopting herd (Alford *et al.* 2006). In Brazil, Mercadante *et al.* (2015) evaluated the methane emissions of Nellore animals divergent in RFI (high and low RFI) and concluded that there was no evidence to suggest that highly efficient animals release less enteric methane, even with lower DMI and the same performance, than their inefficient counterparts.

Unlike dairy cattle, the profile of changes in the relative relevance of trait categories is more similar among RFs, although the magnitudes of the changes vary. The general trend in changes between current and future climate for the categories of traits defined for beef cattle is shown in Fig. 3 and File S6. Overall, the RFs would increase the relative relevance of *environment*-, *adaptability*- and *health*-related traits at the expense of reducing the relative relevance of traits related to *workability*, *maternal ability*, *calving*, *reproduction* and *performance*. Regarding *efficiency*-related traits, even though all the RFs would still select their animals to improve these traits, some farms (SRUC-KA, ESL, INRAE-SLP and UCD-LTGP) would increase their relative relevance and others (NWFP, INIA-PAP and KRS) would decrease their relative relevance in favour of others. In the case of INIA-PAP, the RF with the highest increase (30% compared with relevance in the current climate) in *adaptability* traits, this is driven by the expectation that climate change will affect temperate forage species and livestock production by increasing heat stress for animals, limiting access to water, lowering feed quality and increasing the risk of animal diseases, among other issues. For this reason, traits associated with animal adaptability, resilience and resistance to hotter conditions become more important in a climate change scenario, alongside appropriate feeding strategies. Conversely, UCD-LTGP would put greater emphasis (11%) on *efficiency* traits, as well as on *health*-, *environment*- and *adaptability*-related traits (5–8%; at the expense of *performance*-related traits) because they are experiencing sustained expansion of the dairy herd, which would imply that a greater quantity of beef in Ireland will originate from dairy. Therefore, bulls will be ranked according to their estimated genetic potential for a high-value carcass produced in an efficient manner with minimal repercussions on the dairy cow in terms of milk, health and reproductive performance. Similarly, INRAE-SLP would increase (11%) the relative relevance of *efficiency*-related traits (frame and feed efficiency), driven by the need to select small-frame animals with lower nutritional requirements in view of the decline in grassland production and grassland nutritive quality as a result of high temperatures and increased climatic variability.

Sheep systems

Lambs' *growth rate* (including *days to finishing*) and *kill-out percentage* maintained their high priority, except at NWFP, which reduced the priority of *growth rate* and *carcass weight* in a future scenario in favour of other traits. *Carcass quality* was more favourably selected by NWFP (medium priority), whereas SRUC-KA would increase the priority of *carcass fat and muscle* from low to medium, which may relate to the quality parameter highlighted for beef with changing consumer preferences. *Wool quality* would stay as a low-priority trait for UWA-FF to keep the low fibre diameter, but they would also include *feed conversion efficiency* in their selection program, with a high priority on selecting animals that are most feed efficient across a range of likely feed scenarios in a lifetime, highlighting the normal challenging conditions expected in this part of Australia. Similarly, SRUC-KA would also start selecting for *feed efficiency* on pasture, with medium priority, and would increase the relevance of *ewe mature LW* (from medium to high). NWFP would start using *ewe mature LW* as a high priority trait, whereas *feed efficiency* would remain a key trait.

Fertility-related traits will maintain their relevance in the future scenario. In addition, NWFP will start prioritising lambing traits to focus more on *earlier and easier lambing outdoors* and finishing more lambs before warmer months in summer to avoid potential issues with forage availability. *Maternal ability*

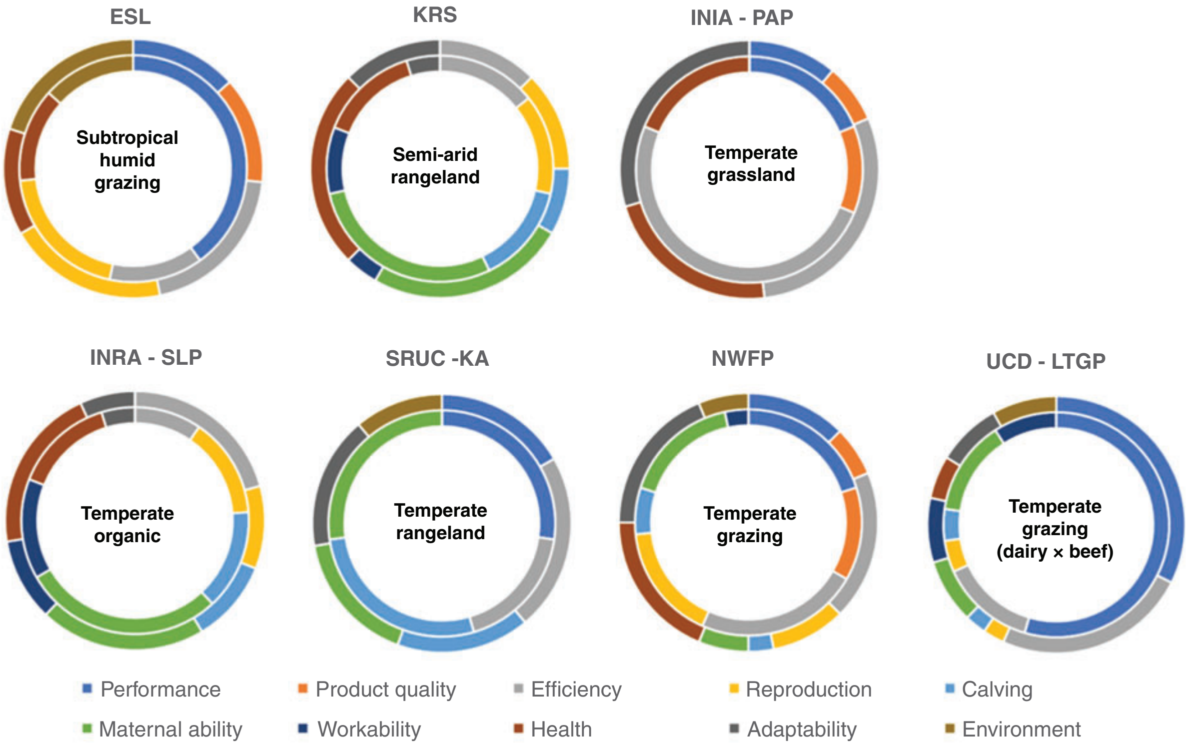

Fig. 3. Relative relevance for selection of traits categories in beef cattle within the different research farms in the current climate (inner circle) and in a future climate change scenario (outer circle; increased global surface warming of 2°C by 2046–65). Individual traits within each of the 10 categories were ranked as low, medium and high priority, and assigned 1, 2 or 3 points respectively. The sum of points for each category was expressed as a percentage of the total points for each research farm. ESL, Embrapa South-east Livestock, Brazilian Agricultural Research Corporation; HRC, Henfaes Research Centre, Bangor University; INIA-PAP, National Institute of Agricultural Research – Palo a Pique research farm; INRA-SLP, Institut National de Recherche pour l'Agriculture, l'Alimentation et l'Environnement - Saint Laurent de la Prée research unit; KRS, Kapiti Research Station, International Livestock Research Institute; NWFP: North Wyke Farm Platform, Rothamsted Research – North Wyke; SRUC-KA: Kirkton and Auchtertyre upland research farms, Scotland's Rural College; UCD-LTGP: Lyons Farm Long-term Grazing Platform, University College Dublin.

is still prioritised for the climate change scenario, and even though KRS decreased the priority of this trait (from high to medium), it would start including *unassisted lambing* in its selection process. HRC would start selecting for ewe efficiency by including the indicator *kilogram lamb weaned per kilogram ewe LW* in its selection process and with a high priority. Similarly, SRUC-KA would continue to assess efficiency using its multitrait selection index, which aims, in part, to reduce *ewe mature size* while improving *lamb growth*. For UWA-FF, going into the future scenario the only reproduction trait listed is *fertility/reproduction* (high priority). However, it is important to realise that this is a general trait that can be achieved by selecting on a combination of individual traits, including the others listed in File S5, namely *number of lambs reared* (optimal), *percentage of lambs reared*, *outdoor lambing* (*lambing ease*, *maternal ability*), *unassisted lambing* and *maternal ability*. Obviously, a choice must be made because too many traits in an index limits the gain in each individual trait, so UWA-FF will have to choose a trait(s) that is easy and cheap to measure, has strong estimates of heritability and genetic correlations. At this stage, the most likely candidate traits are the *number of lambs born unassisted*, the *number of lambs reared* (optimal) and *maternal ability*.

Traits associated with resistance to diseases and adaptation to warmer or more variable climates will become increasingly important in a future climate change scenario. *Resistance to flystrike and worm*s continues to be a high priority for UWA-FF, for the same reasons that these traits are a high priority in the current climate. The same applies to KRS, SRUC-KA and HRC. *Resistance to foot rot* would be of medium priority for SRUC-KA and HRC, and HRC will also include *fluke resistance* in the selection process. All RFs will prioritise *heat tolerance* (including *climatic resilience* and *wool shedding*, except UWA-FF for the value of the wool). UWA-FF would add *robustness* or *versatility* with the aim of identifying animals that are versatile to achieve high lifetime performance in the face of more variable and diverse environments. UWA-FF's strategy, based on its more extreme system and large number of animals, would align to selecting animals that require the least amount of external 'help' to make them 'fit' (optimising Genotype × Environment × Management) or with '*easy care*' (low labour cost, low medication cost, low nutrition cost). Finally, *GHG emissions* would be another relevant trait for SRUC-KA, NWFP and UWA-FF with low and medium priority. According to Hegarty *et al.* (2010), subject to economic

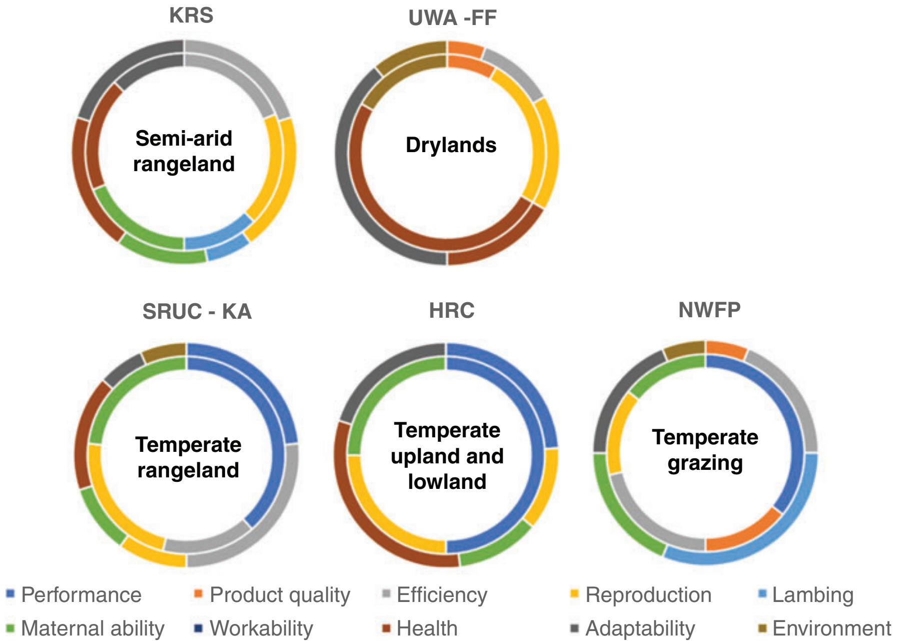

Fig. 4. Relative relevance for selection of traits categories in sheep within the different research farms in the current climate (inner circle) and in a future climate change scenario (outer circle; increased global surface warming of 2°C by 2046–65). Individual traits within each of the 10 categories were ranked as low, medium and high priority, and assigned 1, 2 or 3 points respectively. The sum of points for each category was expressed as a percentage of the total points for each research farm. HRC, Henfaes Research Centre, Bangor University; KRS, Kapiti Research Station, International Livestock Research Institute; NWFP: North Wyke Farm Platform, Rothamsted Research – North Wyke; SRUC-KA: Kirkton and Auchtertyre upland research farms, Scotland's Rural College; UWA-FF: The University of Western Australia Future Farm 2050.

enticements and penalties, genetic improvement for methane emissions is desirable and should be pursued because it offers one of the few ways of modifying emissions from sheep in the extensive grazing environment where targeted nutritional management is difficult. Changes in optimal management need to be accounted for when calculating how the profitability of a farm is affected by changing traits of animals (Groen 1989). For example, among sheep-producing regions in Western Australia, there are large differences in the amount and variability of pasture growth within and between years, which can affect the optimal management of livestock. In turn, this may also affect optimal breeding objectives for these regions; they should be customised depending on variation in pasture growth across years (Rose *et al.* 2015). Therefore, breeding objectives for high or low pasture growth reliability should have more emphasis on LW traits and the number of lambs weaned; objectives for medium reliability of pasture growth should have more emphasis on wool quality.

The general trend in changes between current and future climate for the categories of traits defined for sheep is shown in Fig. 4 and File S6. All five RFs producing sheep concurred in increasing the relative relevance of *adaptability*-related traits, and three farms would also increase *efficiency* traits. HRC would put its greatest emphasis on increasing *health* traits (32% compared with relevance in the current climate). This is driven by the fact that liver fluke, lameness and parasitic worms already have huge economic cost to the sheep sector, and all three are likely to proliferate under a future climate of warmer, wetter winters. In the case of UWA-FF, even though *health*-related traits would still be important in the future climate change scenario, their relative relevance would decrease in favour of increasing the emphasis in *adaptability* traits (39%). This change in emphases relies on the expectations that climate extremes will have both direct and indirect effects on livestock production and health, with serious threats arising from prolonged drought and reduced land area available for pasture, where more resilient, heat-tolerant and robust animals will be required. Another remarkable change in traits relevance profile is seen for NWFP. This RF would notably increase the relative relevance of *lambing* (31%) and *adaptability* (19%) traits to raise sheep more suited to the future climate; that is, producing sheep that are heat tolerant, early lambing and early finishing (before warmer and dry months), adapted to outdoor lambing and with lower emissions.

Changes in feeding strategies

Facing a more challenging environment in the context of climate change, with increased average air temperature and the occurrence of more severe events (IPCC 2013), would necessarily imply modifying, adapting and/or improving feeding strategies to match future livestock demands. These potential changes are summarised in Table 2 for all the RFs and include using or producing new forage species or varieties or mixtures with

Table 2. Feeding strategies for the current climate and for changes predicted under climate change scenarios for the different farm platforms
Dairy 1, Massey University; ESL, Embrapa South-east Livestock, Brazilian Agricultural Research Corporation; HRC, Henfaes Research Centre, Bangor University; INIA-PAP, National Institute of Agricultural Research – Palo a Pique research farm; INRAE-AM, Institut National de Recherche pour l'Agriculture, l'Alimentation et l'Environnement, Aster-Mirecourt research unit; INRAE-SLP, Institut National de Recherche pour l'Agriculture, l'Alimentation et l'Environnement – Saint Laurent de la Prée research unit; KRS, Kapiti Research Station, International Livestock Research Institute; NWFP: North Wyke Farm Platform, Rothamsted Research – North Wyke; SRUC-KA: Kirkton and Auchtertyre upland research farms, Scotland's Rural College; UCD-LTGP: Lyons Farm Long-term Grazing Platform, University College Dublin; UWA-FF: The University of Western Australia Future Farm 2050; UWP-PF: UW-Platteville Pioneer Farm, University of Wisconsin; TMR, total mixed ration; MIG, management intensive grazing

Farm platform	*Current climate*	*Climate change scenario*
Dairy 1	Pasture grass/legume, lucerne, plantain, chicory and supplementary crops (brassica and maize silage)	New pasture varieties and crops to reduce emissions and improve N use efficiency
INRAE-AM	Maximising grazing time during the season and producing silage and hay from permanent pastures	Maximising grazing and hay, with no silage (wet conservation), from both permanent and temporary pasture (cultivated area only for producing human food)
UWP-PF	TMR in confined and TMR and grazing for MIG	Changes in feeding time (at night when cooler) for confined and with added high energy-dense feed for MIG (reduce heat production)
ESL	Dairy: tropical forages for grazing, silage in winter and concentrate in milking parlour Beef: tropical grasses for grazing with different strategies	Utilisation of genotypically and phenotypically adapted forages and crops plus feed conservation for extreme event and shading (trees)
KRS	Sufficient high-quality forage (grazing and hay) with strategic supplementation	Better rotational grazing and building up of a hay stock to ensure sufficient good-quality feeding over the course of the year with the aim of overcoming extreme (drought) years
INIA-PAP	Pasture base all year-round and strategic supplementation with grain, adjusting the livestock strategy according to feeding resources	Use of specific pasture for particular purposes (e.g. summer grazing), improved C_4 forages (higher fibre digestibility), improving forage species based on resilience, strategic grain supplementation, better use of crop residues, adjusting stocking rates and developing adapted systems (livestock–forestry integration, annual vs seasonal systems)
INRAE-SLP	Grazing and hay production from permanent and temporary grassland (grass and legume), mixed cereals–legumes silage and alfalfa hay in a crop–livestock system	Permanent grassland hay, alfalfa hay (in the crop rotation), mature grass in summer (reeds), between-crop and crops residues, and straw if necessary
UCD-LTGP	Perennial ryegrass, perennial ryegrass plus white clover and a multispecies sward containing perennial ryegrass, timothy, white clover, red clover, chicory and plantain grazed *in situ* Grass swards are managed using grass allocation software in conjunction with weekly measurements of available herbage in the swards Silage conserved from these pastures is fed over winter with strategic concentrate supplementation, depending on silage quality, to support the growth of young stock (0–1 years old) or to produce finished beef carcass	Low-input swards, drought-tolerant and flood-resistant swards, bioactive forages, lower protein forages with increased rumen-undegradable protein Strategic supplementation of methane-mitigating feed additives
SRUC-KA	Rangeland grazing, semi-improved grasslands, improved grasslands (for silage) and strategic supplementation with concentrates (winter–early spring)	No change is predicted under the climate change scenario. This herd is already well adapted to and primarily reliant on the rangeland grazing resource throughout most of the year (generally April–December) On-farm-produced silage and a small amount of imported concentrate feed are all that is required during the late winter period
NWFP	Grazed permanent pasture and grass–legume temporary leys, pasture silage, strategic supplementation with by-products during winter (beef cattle), mineral supplementation	Nutritional improvement of main forage species, drought-resistant swards (multifunctional approach (ionomics)), use of flood- or waterlog-tolerant plant species varieties, strategic supplementation by-product utilisation for growth rate of cattle (<20 months), grazing paddock system plus conservation improvement, reduce ewe concentrate inputs before lambing, agroforestry (shade and C capture), feed silage or cut and carry grass or forage to housed stock during periods of heat stress risk, feed concentrates to lambs before weaning to maximise lamb sales before potential periods of drought
UWA-FF	Forages that reduce methane emissions, perennial forages, native plants for delivering biodiversity and forages that inhibit worms	Forages that reduce methane emissions, perennial forages and drought-resistant native plants
HRC	Set-stocking of medium-productivity pastures, supplementation to all twin-bearing ewes and little to no conservation as grass supply is managed, mineral supplementation of all ewes to correct for deficiencies	Rotational grazing in lowlands to optimise grass supply and demand profiles, use of multispecies swards more resistant to drought and flood and to improve mineral availability to livestock, grass conservation (hay and silage) for supplementary feeding in times of low productivity

improved nutritional value to reduce environmental impact and/or be more tolerant of or resistant to drought, salinity or flooding (Abberton and Marshall 2005). There would also be changes in forage conservation strategies (balance between silage and hay in different regions) and increasing the amount of forage conserved to cope with extreme events (Bernardes *et al.* 2018). As countries warm up, systems may adapt by modifying feeding times to avoid warmer hours of the day, increasing the energy density of diets to reduce heat production and incorporating shade through strategic tree planting to reduce the risk of heat stress (Dunshea *et al.* 2017). Improving grazing management (i.e. adopting rotational grazing or improving the efficiency of the current rotational systems, adjusting stocking rates), selecting C_4 grass species, incorporating multifunctional swards and bioactive forages and changing supplementation strategies (timing and type) are also proposed for the future scenario (Table 2). C_4 grasses are more efficient in the use of resources (water and nitrogen), but typically have more lignin and less protein content than C_3 grasses, so strategies to improve nutritional value are required. Climate change will have contrasting effects on these two types of grasses: elevated carbon dioxide has little effect on photosynthesis in most C_4 plants, but leads to higher yield in C_3 plants, whereas warming decreases the yield of C_3 plants over and above that seen in C_4 plants (Lattanzi 2010). Therefore, there is substantial potential to genetically improve C_4 grasses, harnessing their advantages (efficiency of use of resources) and overcoming their limitations (nutritional quality) under climate change (Capstaff and Miller 2018).

Climate change will modify the environment in which forage species will grow, namely there will be: (1) elevated carbon dioxide levels in the atmosphere; (2) elevated air, water and soil temperatures; (3) changes to precipitation patterns; (4) increased environmental variability; and (5) changes in species distribution (Abberton *et al.* 2008). In addition to selecting *resilience* within animal traits, Bullock *et al.* (2007) proposed that introduction of resilience at the field scale, such as incorporating diverse forage species within grasslands or integrating crops, livestock and forestry, would instil higher hierarchy resilience (e.g. within the food chain). Drought tolerance, WUE and flood resistance can be achieved either by improving existing forage species through plant breeding or selecting plant species to exhibit the required traits (e.g. the use of multifunctional swards that are deep rooting, diverse in seasonality of production and have better nutrient use efficiency and forage quality; Abberton *et al.* 2008). Implementing integrated crop–livestock systems or CLFi systems will also provide greater resilience. These approaches will increase the biodiversity and/or lead to the re-establishment of grasslands and provide broader ecosystems services (e.g. increase water infiltration rates, thereby reducing downstream flooding). Under the climate change scenario there will also be continually increasing demands on land, especially productive arable land, which will decrease the availability of human-edible crops to livestock. Yet, there will also be opportunities for improved integration of livestock into arable systems to combat environmental and market shocks (e.g. through novel rotations including grazed grass leys) to increase the resilience of arable systems in terms of soil quality, nutrient utilisation and combating weeds, pests and diseases (e.g. sheep grazing as part of arable rotations to combat black grass). The outcome will be a greater emphasis on the role ruminants play as part of integrated systems and/or in using waste streams (by-products from industry) and in making use of land that is not suitable for growing crops (Van Zanten *et al.* 2018; Wilkinson and Lee 2018). Again, genetic improvement of the animals will be essential under this new production environment, where more targeted and strategic supplementation is required (Eisler *et al.* 2014; Wilkinson and Lee 2018).

Breeding objectives in context

The economic value of traits has historically been the driver for genetic selection in dairy systems. From the 1930s to the 1970s, the emphasis of selection was solely on increasing milk production (Miglior *et al.* 2017), driven by profitability. In the past two decades, many countries have shifted towards more balanced selection objectives by assigning more economic weight to other non-yield traits (Miglior *et al.* 2005), such as fertility and longevity. Despite this recent shift in prioritised traits, the US saw a 3.8-fold increase in annual milk yield per cow from 1950 to 2007, going from 2400 to 9200 kg (Knaus 2009), with a negative effect on the fertility and longevity of cows. This sustained increase in milk production per cow has led to a consistent overall increase in milk production in the US, primarily from animals kept for the most part in a stall-bound, confined environment and fed large amounts of concentrates (Knaus 2009), with higher production costs compared with pasture-based systems (e.g. New Zealand, Ireland; Wilkinson *et al.* 2020). Therefore, farmers have to supply enough milk to make money, given the high feed costs (Whetstone 2019). Since the end of the milk quota system, an oversupply in the European Union and in the rest of the world is putting deflationary pressure on farm gate prices. Consequently, the greatest challenge for the dairy sector resides in its lack of effective instruments to prevent damaging surplus of production (McCullough 2016). For example, 10% and 2.4% volume increases in New Zealand and the USA, respectively, created an 11 million ton milk surplus on the world market in 2016 (McCullough 2016), even affecting organic farmers (grazing-based with low production but greater efficiency and profit) by decreasing milk prices (Parsons 2018). From a global market perspective, it may not be sensible to pursue increased milk production. More emphasis should be put on other relevant traits such as fertility, conformation, health, longevity, workability (i.e. temperament and milking speed) and calving (Miglior *et al.* 2017). It is worth noting that dairy systems are important for global beef supply, and surplus dairy calves are an important co-product. The drive to high-yielding milking cows comes at the cost of less-efficient beef production (Styles *et al.* 2018; Vellinga and de Vries 2018; Soteriades *et al.* 2019). Therefore, breeding objectives should ideally evaluate wider dairy beef production efficiency (i.e. the ability of dairy cows to produce productive beef-fattening calves, with suitable cross-breeding). Novel traits should be considered for both beef and dairy cattle with the aim of improving efficiency and value, increasing nutrient provision for humans, reducing environmental impact and improving animal welfare (i.e. feed conversion efficiency, nutrient content of products, methane emissions, nitrogen use efficiency, heat tolerance and resistance to disease and parasites).

Global beef and sheep production is characterised by a huge diversity in terms of production systems and biotypes. Consequently, a wide range of breeding objectives with diverse traits is used. Most breeding objectives are suboptimal due to a lack of accurate estimates of breeding values on certain traits, mainly fertility, feed intake and efficiency, meat quality and animal health (Berry *et al.* 2016). Unlike dairy production, where Holstein–Friesian is the predominant breed in temperate climates, beef cattle comprise numerous different British and Continental breeds of *B. taurus*, whereas *B. indicus* and *taurus–indicus* crosses are preferred in hot environments (Berry *et al.* 2016). In addition, dairy × beef calves are common in many production systems around the world that are oriented to meat production, which would require a more integrated breeding strategy (for dairy cows). Similarly, sheep present a very broad range of genotypes, with hundreds of breeds adapted to a wide range of agroclimatic regions and nutrient availability (Peter *et al.* 2007). All these genomic differences between biotypes makes future genomic selection more challenging. Therefore, it becomes relevant to work towards producing accurate genetic and genomic breeding values for traits particularly suited to different biotypes. This wide spectrum of biotypes varies widely in body size; therefore, when considering the wide diversity of environments and management practices within the global beef and sheep industry, the breed or cross must be carefully chosen in each case to obtain the animal size to maximise efficiency (Arango and Van Vleck 2002) and minimise biotic stresses (Elayadeth-Meethal *et al.* 2018). In addition, there is a strong environment × genotype interaction component (Morris *et al.* 1993) that must be considered when assessing candidates for selection. Hence, a genotype that is superior to another under certain evaluation conditions (e.g. progeny tests in a controlled environment with individual pens and automatic feeders with homogeneous high-quality diets) may not keep its superiority when facing more restricting conditions, such as rangeland grazing or winter forage diets (hay, silage), where there may be variability in forage quality and competition with other animals for the best-quality forage.

There are other aspects of the food chain that need to be considered under current and future production circumstances in order to set up appropriate breeding programs for livestock improvement. One vital aspect is the efficiency of the use and conservation of non-renewable resources, which is key for sustainable food production. Because of the complex interrelationships between the different components, it is necessary to assess environmental impact using more than one indicator of ‘ecological footprint’ (Navarrete-Molina *et al.* 2019). This will help assign an economic value to traits that have no direct economic impact (e.g. GHG emission, water usage, biodiversity) in order to give their correct weight within breeding objectives. For example, Navarrete-Molina *et al.* (2019) calculated the economic cost of GHG emissions and the blue water footprint (BWF) generated by cattle fattening production systems in Mexico’s arid Comarca Lagunera agroecosystem and found that the economic cost of BWF was 115-fold that of GHG emissions. Therefore, traits related with emissions and WUE would have different economic values in the breeding objective depending on production circumstances.

The effects of soil degradation on human food production and the environment are increasingly driving sustainability debates because of the extent and intensity of the degradation. Soil erosion and its negative effect on soil health (loss of organic carbon content) reduce agricultural production capacity and result in environmental pollution, with the movement of vital nutrients from the land into water courses and the atmosphere. Rainfall energy is the prime cause of erosion from tilled or bare soil (Zuazo *et al.* 2003; Pulley and Collins 2019). Permanent soil cover by forage plants is highly effective in reducing soil erosion (Teague *et al.* 2016), and ruminants consuming only grazed forages under appropriate management can result in more carbon sequestration than emissions. Zuazo *et al.* (2003) emphasised that incorporating forages and ruminants into regeneratively managed agroecosystems can raise soil organic carbon, improve soil ecological function by minimising the damage caused by tillage and inorganic fertilisers and biocides, and enhance biodiversity and wildlife habitat. As mentioned earlier, some of these positive outcomes could also be achieved by integrating crops and livestock into rotation systems. The use of locally adapted ruminant livestock would be of benefit in improving the sustainability of production systems in these environments, particularly as part of long-term mixed rotation farming. According to Provenza (2008), there will be a need to produce livestock in systems that match seasonally available forages with production needs, and that match animals anatomically, physiologically and behaviourally to landscapes (i.e. locally adapted livestock). As highlighted by Eisler *et al.* (2014), it is particularly important to consider the advantages of exploiting local genetic resources (i.e. livestock already adapted to local areas), and then using genetic or genomic selection to boost the production of animals that are already adapted to their climates and resistant to local diseases.

The world population is expected to reach 10 billion people by 2050 (Holt-Giménez *et al.* 2012) and global consumption of ruminant meat (beef, lamb and goat) is projected to increase by 88% between 2010 and 2050 (Ranganathan *et al.* 2018), a growth rate in excess of the 50% increase in global population. Each year, half the total world food production (amounting to 1.6 billion tons) is wasted (Ishangulyyev *et al.* 2019). Furthermore, individual overconsumption globally is feeding a metabolic syndrome catastrophe for the human population. Obesity is a double jeopardy of misusing valuable food resources and driving resources towards medical support. This total wastage could feed in excess of 3.5 billion people. In developing countries, food waste accounts for 44% of total food production, with 29% of the food produced lost in production, handling and storage (two-thirds of the losses in developing countries), whereas in developed countries the total food waste is 56%, with 28% of the food produced wasted at the consumption stage (half the losses in developed countries; Ishangulyyev *et al.* 2019). Preventing this wastage in the first place is perhaps the starting point for ensuring future food security. In addition, one-third of productive cropland area is used to produce feed for livestock (FAO 2006), forming another form of ‘food waste’. If the calories diverted away from direct human consumption by feeding cereals to animals were used instead as human food, there is a potential to improve food security further without causing land use change. This change would exploit the unique feature of ruminants to convert non-edible human food (e.g. food industry by-products and forage produced from lands not suitable for growing feed for humans) into nutrient- and calorie-dense food for humans. Of course, monogastric livestock (pigs and poultry), which require a higher-quality feed (protein and energy availability) but convert at a higher level of efficiency than ruminants, will also play a vital role in using higher-value by-products as part of a circular economy, but they fall outside the scope of the present study. It is also important to note that issues related to global food security are not only about production and efficiency (reduced waste), but also about poverty and inequality. Even though these aspects are also beyond the scope of this study, it is worth citing the conclusion of Holt-Giménez *et al.* (2012):

> To end hunger we must end poverty and inequality. For this challenge, agroecological approaches and structural reforms that ensure that resource-poor farmers have the land and resources they need for sustainable livelihoods are the best way forward.

Finally, probably the most difficult aspect of production circumstances to predict for future are market trends, driven by consumer preference and influenced by the media. This will delineate product demand and influence food types and prices. According to an online study conducted in the USA, 49% of adults accessing online resources reported learning about food through social networks, whereas 40% gained awareness through websites, apps or blogs, discovering, learning, sharing and talking about food online (Hartman Group 2012). Therefore, this is a factor to consider when trying to predict future food baskets. Conversely, there is growing interest in pasture-based and organic products because these systems are perceived as more healthy, natural and with higher animal welfare than confined intensive alternatives (Wilkinson *et al.* 2020). This may represent a driving force for a country's selection strategies (e.g. Uruguay, exporting most of its meat), targeting niche markets that value produce quality. This will potentially increase the relevance of ruminants adapted to grazing conditions, encourage the adoption of organic production approaches and increase the value of agroecological systems that not only provide a grazing environment to ruminants, but also, under appropriate management, may provide additional ecosystem services to wider society. The trade-offs between these positive aspects and productivity, if any, should also be considered when assessing the relevance of each trait in future breeding objectives.

Conclusions

The selected RFs, which covered diverse agroclimatic conditions, prioritised different traits in their breeding objectives under current and future predicted climates aligned to the different challenges of their environment. However, certain traits were common among the RFs, particularly those related to efficiency, reproduction, resistance to diseases and heat tolerance. In this study we identified key traits that are and will be prioritised for each RF in their particular production circumstances, and the same exercise can be performed for other relevant productions systems (e.g. pig and poultry, arable production or extensive land-based industries such as energy and fibre). Such approaches are needed to define the role ruminant livestock have in future sustainable food systems, which will optimise resource use efficiency, protect the environment and ensure an adequate supply of key nutrients to a growing human population.

Conflicts of interest

The authors declare no conflicts of interest.

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