10.1071/RD20205_AC

Supplementary Material: *Reproduction, Fertility and Development*, 2021, 33(1–2), 1–19.

Supplementary Material

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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File S1 – Description of the farm platforms

Dairy 1 farm (New Zealand, Temperate grazing – dairy) – (as summarised by Harrigan (2017)) encompasses 142.7 ha (119.7 ha effective) of free-draining recent alluvial soils. This farm produces milk with a spring calving herd comprising 75 Friesian, 56 Jersey and 119 Friesian x Jersey crossbred cows under once a day milking during the entire season, all selected using a once-a-day selection index. The cows are milked through a 24 a-side herringbone shed. All cows have access to fresh perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) pasture with supplementation as required. Supplementation crops include mixtures of plantain (*Plantago lanceolata* L.) and chicory (*Cichorium intybus* L.), turnips (*Brassica campestris ssp. Rapifera* Metzg.) and maize (*Zea mays* L.).

ESL - Dairy cattle (Brazil, Sub-tropical grazing and parlour feeding – dairy) – (as summarised by Berndt *et al.* (2014)) milk production system is based on intensive rotational grazing in 38 hectares. The herd rotates in small paddocks electrically fenced within three sets of perennial tropical grass pastures (*Panicum maximum* sp.) all year round. Milking cows receive maize silage only during the winter-dry season (May to October). Concentrate supplement is furnished according to milk production at parlour. Pastures are chemically fertilized after grazing according to agronomic requirements to maintain high production of biomass. The herd is composed of Holstein purebred and Holstein x Jersey crossbred cows at 6.6 LU/ha stock rate returning 7,930 kg of milk /lactation.

ESL - Beef cattle System 1 (Brazil, Sub-tropical intensive grazing – beef)- (as summarised by Oliveira *et al.* (2018)) irrigated high stocking rate system (IHS) is established with *Panicum maximum* tropical grass and managed as rotational grazing system (3-d occupation and 33-d rest cycle). The total area is 7 hectares, divided in four systems of 1.75 ha each, divided in 12 paddocks and receives 660 kg urea-N ha^{-1} $annum^{-1}$. Irrigation is based on the climatological water balance method and once a year the area is over-seeded with a mix of *Avena byzantina* and *Lolium multiflorum*. The stocking rate is 6.6 LU/ha/y with final body weight ca. 531 kg, and average daily gain of 0.530 kg/d.

ESL - Beef cattle System 2 (Brazil, Integrated crop-livestock-forest systems - beef) – (as summarised by Bernardi *et al.* (2018)) is based on an integrated system covering 30-ha area which includes five different combinations of grazing strategies: i) intensive rotational grazing with tropical Palisade grass (*Urochloa decumbens*); ii) crop-livestock integration (CL): each year 1/3 of the area is renewed by sowing maize intercropping with Palisade grass; iii) crop-livestock-forest integration (CLF): planted with *Eucalyptus sp.* in rows (15 m in 2 x 2 formation); iv) pasture-forest (LF): Palisade-grass and Eucalyptus; v) extensive permanent grazing. The systems 1 to 4 are divided into 6 paddocks. The stocking rates of integrated systems are higher than the extensive systems (2.6 and 1.4 LU/ha/y, respectively).

HRC (UK, Upland and lowland improved and rough grazing - sheep) - (as summarised by Marsden *et al.* (2018)) lowland-upland sheep enterprise is typical of the region and comprises 30 ha productive lowland pasture + 70 ha upland pasture (300 m above sea level). The typical sheep breed is the Welsh Mountain. Fertiliser and lime are applied to lowland pastures according to UK recommendations, with no inputs to the upland pasture, for which payments are received through the national agri-environment scheme (AES). HRC has 1,600 ewes, with a lambing percentage of 110% (and rearing percentage of 100%). Ewes are set-stocked in the lowland and upland, with additional feed (home-grown silage) and bought-in concentrates supplied as required (predominantly to twin-bearing ewes) during winter and early spring. Ewes graze some parts of the upland pasture at relatively high grazing intensities (2 LU/ha) during some parts of the year and are removed from some parts of the upland pasture to provide suitable habitats for ground nesting birds in return for AES payments. HRC is used extensively for studying the potential for sustainable intensification of sheep production whilst also delivering wider environmental and societal goods in both a research and commercial setting.

INIA-PAP (Uruguay, Pasture-crop rotations – beef (as summarised in Rovira *et al.* (2020)) - evaluates four different pasture-crop rotations in a 150-ha farm platform (33° 15′ 54.4′′ S, 54° 29′ 28.01′′ W): i) permanent pasture, ii) four years pasture – two years crops, iii) two years pastures – two years crops, and iv) continuous cropping, all under no-till technology to address issues of sustainability associated with crop-livestock systems in marginal agricultural soils. Today, with animal protein set to remain a significant part of food demand, the INIA-PAP pursues different pathways of sustainable livestock intensification based on different animal categories and combinations of backgrounding and/or finishing beef cattle on the original pasture-crop rotations. Data from this long-term experiment contributes to predict trade-offs between environmental, economic, and production indicators, enabling timely anticipation of adverse sustainability issues and helping to establish new national policies.

INRAE-AM (France, Organic crop-livestock Agro-ecology – dairy and sheep) – (as summarised by Coquil *et al.* (2009)) has set up dairy cattle grazing system with a logic of autonomy to "do the best with the resources of the environment". The system is designed at the whole system scale with a step by step design approach (Coquil *et al.* 2014). The system is composed of 40 dairy cows of equal numbers of Holstein and Montbeliarde breeds and their replacement heifers. The herd is managed in a logic of strict feed autonomy on 78 ha of permanent meadows. The dairy cows are fed exclusively on grass with maximised grazing over a large part of the year and a hay-based ration during the winter period. Calves are grouped together in the spring to maximise milk production on pasture.

INRAE- SLP (France, Organic crop-livestock Agro-ecology – beef) - (as summarised by Durant *et al.* (2020)) implemented an agroecological transition on a mixed crop-livestock farming system in the marshes of the French Atlantic coast with a ‘step by step’ approach i.e. using continuous improvement of the system. The aim is to experiment agroecological practices adapted to the marshland constraints and to investigate the system sustainability in the long run in terms of environmental, economic and social aspects performances. The system, converted to organic farming, covers an area of 160 ha with 115 ha of permanent wet grasslands and 45 ha of arable drained land. The fields are criss-crossed by a network of freshwater ditches. The herd consists of 55 suckler cows, replacement heifers and calves, feeding entirely by the forage and grains produced on farm. Stocking rate is moderate (0.7 LU/ha of fodder area). Calves, weaned calves and cows are sold on on-farm direct selling, to local traders and to one cooperative. To achieve the agro-ecological objectives, a combination of practices is applied e.g. use of a local and rustic breed (Maraîchine), use of a diversity of plant species and varieties in crops and temporary grasslands to enhance diversity and strengthen resilience, creation vegetation mosaics in grazed grassland to preserve wild biodiversity.

KRS (Kenya – Livestock-wildlife rangeland – dairy, beef, sheep, goats and camel) - (as summarised by ILRI (2019)) is a livestock-wildlife ranching system located in the semi-arid regions of South-Central Kenya. The average rainfall in the region is approximately 500 mm per annum with two distinct wet seasons, often referred to as short and long rains and two distinct dry seasons. The farm covers an area of roughly 13000 ha and is home to approximately 2800 cattle (predominantly indigenous Boran cattle – *Bos indicus*) which are kept in herds of ca. 130 heads. Other animal livestock species are 1500 sheep, 500 goats and 70 camels. The recommended stocking rate in these semi-arid regions is 0.16 LU/ha to cover potentially failing rainy season and to consider enough forage for freely roaming wildlife. The farm is not fenced and is part of an important wildlife corridor between the Nairobi National Park and Amboseli National Park. The ILRI farm pursues pathways of sustainable intensification depending on animal category an includes various strategies of rotational grazing. Besides the commercial production of meat and milk on the farm, animals are regularly used in clinical trials (i.e. proof of principle for vaccine development or immunogenicity studies) as well as source for pure bred animals, (Boran cattle, Red Masai sheep) or cross bred animals (Boran x Friesian heifers or Dorper x Red Masai sheep).

NWFP (UK, Temperate grazing – beef and sheep and intensive housed beef (as summarised in Orr *et al.* (2016)) - comprises three hydrologically independent small-scale farms (‘farmlets’ ~22 ha), each divided into five hydrologically isolated catchments and, together with its own infrastructure (consisting of a silage clamp (for winter feeding), a manure midden and a housing facility for cattle and sheep), is managed separately as a virtual commercial entity. Currently, one farmlet was converted into an arable system (human-edible crops). The remaining two farmlets are beef and sheep lowland pasture-based enterprises for grazing and silage cut, being permanent pasture or grass-legume temporary ley. The aim is to finish beef cattle (Stabiliser breed) at 18-20 months of age based on forage (grazing and silage, with a minimum strategic supplementation) and to sell finished lambs off grass (Suffolk mule ewes x Charolais rams). In winter 2018-2019 an intensive-finishing housed beef system started, aimed at finishing Stabiliser cattle at 12-14 months of age with forage and least-cost commercial concentrate ration.

SRUC-KA (UK, Upland rough grazing – sheep and beef) - where the farming system is focussed on upland (rangeland) sheep and cattle production across 2,200 ha on two contiguous farms, ranging in altitude from 170 m asl to over 1,000 m asl. Livestock consist of ca. 1400 breeding ewes (approximately 1150 Scottish Blackface, 200 Lleyn, 50 hill breed crossbred) and 27 Aberdeen Angus crossbred cows. The grazing land consists of ca. 70 ha of improved grassland and ca. 150 ha of semi-improved pastures in the lower part of the farm and ca. 1,700 ha of unimproved upland moorland grasslands. Stocking densities vary seasonally throughout the year, from between 0.5-1.0 LU/ha on the lowland areas at times during the spring/summer to less than 0.2 LU/ha on the moorlands throughout the year. There is also ca. 300 ha of woodland on the farms, the majority of which was planted over the past 20 years. Key assessments include numbers and weights of animals at each handling event throughout the year. For the sheep, more detailed individual performance information is collected from 400 Scottish Blackface and 200 Lleyn ewes, including: reproduction, health and longevity metrics, growth and carcass quality of their lambs (ultrasound fat and muscle depths, carcass grades). Grass heights and biomass measurements of the grasslands are regularly assessed, as well as environmental measurements (e.g. rainfall, air temperature and humidity, soil temperature and moisture, water depth in watercourses). The agricultural production-oriented research conducted at SRUC-KA is aimed at understanding what may be practical or economically viable, for rangeland and upland land managers to implement, to improve the cost-effectiveness of their production systems and thereby reduce emissions to the environment.

UCD-LTGP (Ireland, Temperate grazing – dairy-beef) - - is a 24-ha grazing platform subdivided into three separate farmlets, each sown with one of three sward treatments. The treatments are a perennial ryegrass sward (PRG) a perennial ryegrass plus white clover sward (PRGWC) and a multispecies sward containing perennial ryegrass, timothy (*Phelum pratense*), white clover, red clover (*Trifolim pratense*), chicory and plantain (MSS). Each sward treatment is stocked at a rate of 2.5 LU/ha with Hereford sired steers born to dairy cows. Each farmlet consists of 4 x 2 ha hydrologically isolated paddocks. These 2 ha hydrologically isolated paddocks are further sub-divided into 1 ha grazing paddocks. Key metrics assessed at the UCD-LTGP include animal growth rate, parasite burden, methane emissions, rumen fermentation variables and rumen microbiome, meat yield and quality, sward botanical composition, DM yield and quality, soil fertility and water quality. The long-term goal is to develop blueprints to support environmentally sustainable pasture-based ruminant production systems.

UWA-FF (Australia – drylands – crop-livestock – sheep) - is located on a 1588 ha commercial farm near Pingelly (S 32° 30’ 23” – E 116° 59’ 31”), in a major agricultural region (the ‘grain belt’) of Western Australia. The climate is Mediterranean, and the average annual rainfall is about 445 mm, most of which falls in the cooler months (April to September). Maximum temperatures can reach 45°C in summer and minimums can be as low as –2°C in winter (with frosts). The major income-generating enterprises are crops (500 ha; cereals, canola (*Brassica napus*), lupin (*Lupinus* sp.); total about 1000 tonnes/y) and grazing livestock (3000 Merino ewes; 3000 lambs/y; 15000 kg wool/y, mostly 18µ). However, the project involves more than agriculture – it embraces biodiversity conservation and restoration, water and soil management, the human environment, and community development. The purpose of UWA-FF is to imagine the ideal farming system for 2050 (for its part of the world) and begin to transform the farm now, all the while remaining profitable.

UWP- PF (USA, housed and grazing – dairy) - (as summarised by Stuntebeck *et al.* (2011)) Pioneer Farm is a 174-hectare farm located near Platteville, Wisconsin (42.711970, -90.378260) in the Northern Mississippi Valley Loess Hills (NRCS MLRA M105) of the midwestern United States. Of the total farm area, 138 hectares are utilized for conventional and no-till crop production and 20 hectares are permanent pasture. The crop rotation includes *Avena sativa* L. (oats), *Zea mays* L. (maize), and *Medicago sativa* L. (alfalfa). Dairy livestock production systems include a 150-head free-stall total confined dairy and a 20-head hybrid grazed dairy herd. Pioneer Farm collects environmental data via an extensive monitoring network which includes: 21 surface-water runoff gauging stations, 12 groundwater monitoring wells, 16 undisturbed soil core lysimeters, one perennial stream gauging station, and one meteorological station. Evaluations are focused on sustainability and resiliency metrics such as soil, nitrogen, and phosphorus loss in runoff, nitrate leaching to groundwater, soil carbon flux, carbon efflux, soil quality, soil health, crop and animal productivity. Collected data is used to support local, regional, national and international research and modelling efforts through participation in the USDA Long-Term Agroecosystems Network and the Global Farm Platform.

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File S2 – Approached followed for each research farm to define the traits (and their priorities) and the feeding strategies included in the current and future climate conditions

Research Farm	***Methodology and drivers***
Dairy 1	***Current climate traits:*** the traits were obtained from the current selection index defined with Livestock Improvement Corporation (the most important breeding company of New Zealand).
	Future climate change traits: the traits were motivated by the implementation of the Climate Action Plan of Massey University to reduce its greenhouse gas emissions in the key areas of energy, buildings, transport, farms and waste and recycling (https://www.massey.ac.nz/massey/about-massey/news/article.cfm?mnarticle_uuid=211623DE-0D48-4C50-BC2A-52213C843D7A)
	Current and future feeding strategies are aligned with the national strategy of New Zealand to reduce methane emissions and nitrogen excretion by the cows (DairyNZ 2020 https://www.dairynz.co.nz/about-us/research/low-nitrogen-livestock-programme/).
INRAE-AM	***Current and future climate traits:*** the priorities were defined by the research group of INRAE-AM according to their own scientific priorities and drivers of the system. Also, they were inspired by the problems found by farmers who visit the research farm or whom they visit. The main driver for the selection of traits are the issues with fertility and reproduction of in spring because of the trade-off between milk production and reproduction functions. Therefore, the objectives are reducing milk production (and increasing milk solids concentrations) and improving reproductive performance, even going as far as opting for crossbreeding with the most problematic animals (future scenario). Besides, INRAE-AM aims to have grazing systems to enhance the value of the grass through grazing. Thus, the system requires animals that are adapted to walking in the paddocks and on the path (small animals with strong hooves to avoid lameness). Facilitating the work of farmers and increasing longevity are also relevant targets, therefore, udder characteristics, temperament, and calving ease are relevant traits.
	Current feeding strategies based on the strict grass-based nature of the farm and on the expertise of the researchers and farmers interacting with the group.
	Changes in feeding strategies were based on past experience of the research groups and reasoning about the place of the cattle herd within a diversified system. They also remobilised testimonials from producers to define practical modalities.
UWP-PF	***Current and future climate traits:*** the traits and priorities were primarily developed through discussions with local farmer-led watershed groups and individual farmers operating dairy grazing, conventional dairy milking operations, and other systems. These discussions were informal, face-to-face, *ad hoc* meetings which were iterative in nature. The publication "Climate Change and Global Dairy Cattle Sector: The role of the dairy sector in a low-carbon future" (FAO 2019) was used as a starting point to initiate the discussion of scenarios.
	Current and future feeding strategies were obtained from the same activities as the traits
ESL	***Current and future climate traits:*** Researchers experience along with the results of a comprehensive study carried out by the whole research team of ESL (42 researchers and more than 20 research assistants) from August 2018 to May 2019 to determine current problems and future challenges to overcome in the animal production systems of Southeast Brazil. The study was conducted as follows: i) Definition of production and market trends through a literature survey, ii) Analysis of external issues by consulting stakeholders of ESL (28 experts from 24 different institutions: researchers and academics of Agriculture and Animal Sciences, farmers, extension professionals, government authorities and people from supply chains, as well as from the dairy and beef industries), iii) Listing relevant problems of dairy, beef, sheep and agriculture of Southeast Brazil as outcomes of four specific workshops, and iv) Prioritization of problems according to their relevance and impact through the Analytic Hierarchy Process. This multi-criteria method with mathematical algorithms was applied with support of the online tool BPMSG (available at http://bpmsg.com/ahp-online-system).
	Current feeding strategies were defined based upon the researchers' experience on validated animal production systems of Southeast Brazil and utilising international nutrient requirement tables, Brazilian feeds & feeding manuals with tables on the nutritional value of feedstuffs, as well as commercial computational aid tools.

	Changes in feeding strategies were anticipated by applying a decision support system created by Embrapa (available at http://tecnologias.cppse.embrapa.br/scafforragem/) and supported by predictions of the effects of climate changes on agriculture and husbandry (e.g. http://ainfo.cnptia.embrapa.br/digital/bitstream/item/126017/1/PROCI-2015.00018.pdf). The "Embrapa *Scafforragem*" system is an online tool for decision-making, and it is based on building up future scenarios of performance of tropical forages utilized in Brazil. The system takes into account databases on climate changes and generates maps of current and future production levels of forages from 2025 to 2055.
KRS	***Current and future climate traits:*** the traits and priorities were set based on the researchers' experience and knowledge.
	Current feeding strategies: for Kapiti and basically most sub-Saharan African livestock systems feeding is a core constraint currently and also under future climate change. The negative consequences of reduced animals' feed intake on both productivity and methane emissions have recently been highlighted by Goopy *et al.* (2020). Therefore, feeding strategies were set based on the scientific evidence and the researcher and the farm manager's experience. ***Changes in feeding strategies*** were based on the performance assessment of the animals on farm. Indicators of performance are growth rate, calving interval, calving rate, disease resistance and tolerance, adaptability to extreme climatic conditions (i.e. prolonged droughts) over the past > 5 years.
INIA-PAP	***Current and future climate traits:*** both the traits and their prioritisation were defined through discussions within the research team responsible for the farm platform taking into account information gathered by different projects and activities that are frequently carried out by INIA (i.e. identification of demands from the productive sector, technical seminars, farmers discussion groups, etc.). The main drivers for the current climate are i) animals graze all year round, even during periods of low forage availability and/or quality, and ii) meat quality is an important trait to compete in international markets (niches). For the climate change scenario, the key driver was the expected increase in temperature in a current temperate region that would 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.
	Current feeding strategies were defined according to pasture and crop rotations that were set as treatments in the original design of the long-term sustainability experiment started in 1995. The species that compose the different phases of the rotations and the grazing strategy mirror those that are most commonly used by producers in commercial systems, as well as the practice of grain supplementation of animals during winter. More specifically, the current feeding strategies are based on local knowledge about species adaptation to local environment scientifically supported by official and science-based reports about species/cultivars performance, reports from breeding programs of seed forage companies, and projections based on feed budget plans. ***Changes in feeding strategies*** were proposed according to the experience (weaknesses and strengths) obtained during the 25 years of running the long-term experiment (e.g. strategic supplementation trait), forecasts of climate change (e.g. improved C4 forages trait), and environmental concerns of the society (e.g. integrated livestock-forestry systems for more carbon sequestration). Also, specific research has been carried out to quantify the impact of feeding and management alternatives to mitigate the impact of climate change, especially during summer (i.e., species adaptation to changes in environmental conditions, species persistence trials, provision of shade to animals).
INRAE-SLP	***Current climate traits:*** the rustic breed Maraîchine was chosen for the INRA-SLP research farm for its traits (dual-purpose, good dairy capacity and good calving ease, it is fertile and has a good longevity due to few health problems) match with an agroecological management in marshland, and also because they have the objective of taking part in the rescue of an emblematic breed of marshland. The researchers work closely with the breeders of the Maraîchine association to preserve these rustic traits. ***Future climate change traits:*** with the same aim of maintaining the adapted breed, the researchers carried out meetings and discussions with the Maraîchine association and adopted the dominant view: to select small-frame animals with lower nutritional requirements, heat-stress resistant (no trees, harsher conditions), in view of the decline in grassland production and grassland nutritive quality as a result of high temperature and increase of the climatic variability.
	Current feeding strategies were determined by using specific software (INRAtion®) and researcher's expertise. ***Changes in feeding strategies*** were based on discussions and knowledge of the researchers and simulations with simple models based on dry matter requirements and offer in the farm.

UCD-LTGP	***Current and future climate traits:*** The traits included were set in the context of local and national farming practices while demonstrating what is possible to fulfil national policy and ambition in the context of international drivers. Therefore, the traits were selected as they are reflective of the Dairy Beef Index (https://www.teagasc.ie/media/website/publications/2019/A-dairy-beef-index-(DBI)-to-rank-beef-bulls-on-profitability-for-use-on-dairy-females.pdf). The expanding dairy herd, coupled with improving cow fertility, will require a tool that sorts beef bulls based on suitability for use on dairy females. This ranking system should ideally rank bulls on 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.
	Current feeding strategies represent local practice in Ireland, where there is a strong focus on pasture-based production systems. ***Changes in feeding strategies*** were based around discussions with industry experts in the content on future policy as informed by national and international policy.
SRUC-KA	***Current and future climate traits:*** Livestock farming in the Highlands of Scotland faces topographical, climatic and nutritional challenges to growing (lambs and calves) and breeding (ewes and cows) animals. Therefore, ewe and lamb traits included in the current breeding programme are based on a hill sheep genetic selection index, developed at SRUC on SRUC-KA and another research hill farm, which aims to maximise economic returns (Conington *et al.* 2001, 2004). An adapted version of this index, including the same key traits, is used by Signet within the national UK breeding programme for hill sheep (https://signetdata.com/technical/sheep-genetic-notes/breeding-indexes/). The climate change scenario traits then took into account - and expanded via professional discussion - those existing traits to include others considered of additional importance under predicted climate changes. The selection of traits for the cattle scenarios were based upon practitioner knowledge and experience of the cow and calf characteristics required in this harsh environment, with traits influenced under the current scenario by the choice of bulls with appropriate Estimated Breeding Values.
	Current feeding strategies provided in the current climate were based on both practitioner knowledge and research experience gained at the site over the past 50 years. The sheep feeding strategies have also been informed over the past 10 years by detailed knowledge of individual ewe performance over each winter through regular weighing, condition scoring and implementation of alternative feeding, where necessary, as part of a Precision Livestock Farming approach (Morgan-Davies *et al.* 2018). ***Changes in feeding strategies*** for both sheep and cattle were based on professional discussion, taking into account current experience of the livestock on-site, any impacts on performance associated with extreme climate events experienced and recorded in recent years and the likely future climate livestock will be exposed to.
NWFP	***Current climate traits:*** for beef cattle, the definition of traits and their priorities was based on the Stabiliser breed's "Profit Index" (https://stabiliser.co.uk/) and discussion within NWFP livestock cluster, driven by the need of producing more sustainable animals, i.e., economically, environmentally and societal sustainable. For sheep, the definition of traits and their priorities were derived from the experience and knowledge of the NWFP livestock cluster on lowland sheep production and driven by the demand of producing high-quality lambs from efficient and sustainable forage-based systems. ***Future climate change traits:*** both for cattle and sheep, the definition of future traits and their priorities was based on discussions within the NWFP livestock cluster and driven by the necessity of breeding animals more adapted to the hotter and more variable climate and with increased efficiency of production on forage-based systems, with lower environmental impact and still delivering quality food.
	Current feeding strategies represent the production systems currently being tested at the NWFP, which is based on permanent pasture and mixed temporary leys, with self-sufficient forage production and strategic supplementation of sustainable feeds (by-prodducts). ***Changes in feeding strategies*** were defined by the livestock researchers based on future plans of the NWFP in terms of incorporating multifunctional swards to the tested strategies, the expected increase in extreme event (e.g. draught, flooding), the need for keeping harnessing the unique future of ruminant which is upcycling human non-edible feeds (by-product of food industry), and reducing external inputs.

UWA-FF	***Current and future climate traits:*** traits were chosen in the context of the aspects of 'Steps to Sustainable Livestock' (Eisler *et al.* 2014) that are relevant to UWA-FF's production system and to the local socio-geographical environment. We have high expectations of success despite the fact that we are dealing with extensive grazing systems with large flocks, because we are experiencing a technology-led revolution in the generation of genetic data: electronic identification, DNA pedigrees, and automatic recording of phenotype such as body weight and litter size (Martin and Greeff 2011). Thereafter, we were guided towards areas where we know genetic gains can be made, as evidenced by documented genetic variation (known breed differences or within-breed variation) and by robust estimates of the heritability of the trait under consideration, such as methane emissions (Robinson *et al.* 2014).
	Current feeding strategies: in researching alternative grazing systems that mesh with the holistic, whole-farm nature of the UWA Future Farm 2050 project, we have realised the value of Australian indigenous plant species, particularly the deep-rooted perennial shrubs. They are adapted to our climate and soils, and they can be expected to improve the productivity of adjacent pasture by lowering saline ground water level, increasing soil carbon content, and reducing wind speed, lowering soil moisture loss, and providing shelter for soils and plants. As Australian indigenous species, they also provide a reservoir for beneficial invertebrates and increase biodiversity (George *et al.* 2012; Perring *et al.* 2012). In general, they provide far better nutrition over the summer-autumn feed gap than annual pastures (D. *et al.* 2016). Some shrub species offer specific benefits to livestock production, including abilities to combat gastrointestinal nematodes, acidosis and methane emissions (Revell *et al.* 2013; D. *et al.* 2016), all of which are essential for the future (Eisler *et al.* 2014). In addition, during lambing, shrubs become 'edible shelter' with the potential to improve lamb survival in inclement weather (Young *et al.* 2014). Importantly, they improve farm profitability (Monjardino *et al.* 2010).
	Changes in feeding strategies: To predict the future, we extrapolated from the existing knowledge of the new systems based on indigenous plants, outlined above, because we expect strong uptake by industry. This approach was supported by studies with the MIDAS decision-support software, demonstrating the benefits of new feeding strategies (Young et al., 2014), the rate of expected adoption and the value of industry funding for further research into new feeding strategies (Monjardino *et al.* 2010).
HRC	***Current and future climate traits:*** The traits and priorities defined in both scenarios were largely based on experience, moulded by what the market requires in sheep systems, and the need to reduce the costs of production. For instance, labour inputs per livestock unit account for a notable proportion of production costs, therefore selecting for strong maternal traits and lambing ease would be important drivers in many commercial sheep systems. Given the upland nature of HRC, grass production often rapidly decreases when air and soil temperatures reduce in the autumn. Reducing lamb days to finishing is therefore important so to reduce the need for feed supplementation. The market returns for smaller carcasses typically produced in upland sheep systems have been poor for many years, therefore selecting for a higher lamb kill-out weight would help ensure better returns. 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. Not only do these burdens on animal health require greater labour inputs and increased expenditure on treatment drugs, they have knock-on implications for a host of other production attributes such as number of lambs reared per ewe, lamb days to finishing, and carcass weight. Collectively, these could significantly compromise the economic viability of sheep production systems that are already often only marginal.
	Current feeding strategies were largely based on experience, validated with periodic metabolic profiling of sheep bloods over the years. This has identified the need for supplementation of twin-bearing sheep to ensure sufficient energy and protein intakes in the latter stages of pregnancy and during the lactation period. Single-bearing sheep have been found to obtain sufficient supplied of energy and protein from forages. It also reflects the extensive, low-input nature of such systems in terms of supplements and labour. Blood sampling revealed deficiencies in minerals relative to levels advised by veterinarians, therefore all sheep are supplemented prior to breeding.
	Changes in feeding strategies: in the climate-changed scenario, software/decision support systems will be used to aid more accurate budgeting of forage supply/demand profiles, which may be more erratic under greater frequencies of extreme weather patterns. This should lead to reduced need to supplement livestock to compensate for shortfalls in grass

quantity and/or quality. The use of multi-species leys (with deeper rooting profiles) as opposed to conventional ryegrass leys will also help supply livestock with the required minerals, again reducing the need for supplementation.

Dairy 1 farm, Massey University, Palmerston North, New Zealand; ESL: Embrapa Southeast Livestock, Brazilian Agricultural Research Corporation - Embrapa, Sao Carlos, Brazil; HRC: Henfaes Research Centre, Bangor University, Bangor, UK; INIA-PAP: INIA Palo a Pique, National Institute of Agricultural Research - INIA, Treinta y Tres, Uruguay; INRAE-AM: INRAE ASTER-Mirecourt Research Farm (INRAE-AM, French Institute for Agricultural, Food and Environment Research - INRAE, Mirecourt, France; INRAE-SLP: INRAE Saint Laurent de la Prée Research Farm, INRAE, Saint-Laurent-de-la-Prée, France; KRS, Kapiti Research Station, International Livestock Research Institute - ILRI, Nairobi, Kenya; NWFP: North Wyke Farm Platform, Rothamsted Research – North Wyke, Okehampton, UK; SRUC-KA: Kirkton & Auchtertyre upland research farms, Scotland's Rural College - SRUC, Crianlarich, UK; UCD-LTGP: Lyons Farm Long-term Grazing Platform, University College Dublin - UCD, Dublin, Ireland; UWA-FF: UWA Future Farm 2050, University of Western Australia - UWA, West Pingelly, Australia; UWP-PF: UW-Platteville Pioneer Farm, University of Wisconsin – Platteville, Platteville, US.

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File S3 – List of traits for dairy cattle relevant to the research farms[1] in the current climate and in a future climate change scenario (increased global surface warming of 2 ºC by 2046-2065), and their prioritisation for selection (low priority – lightest square, high priority – darkest square, medium priority – intermediate colour square; blue for desired increases, red for desired decreases).

Traits & climate	Dairy 1 – Massey	INRAE – AM	UWA-PF – Confined	UWA-PF– MIG[2]	ESL	KRS
Current climate						
Milk production						
Milk production consistency (despite feed quality)						
Crossbreeding (adapted x milk specialized)						
Milk fat production						
Milk protein production						
Milk fat percentage						
Milk protein percentage						
Somatic cell score						
Body condition score						
Carcass quality						
Liveweight						
Feed efficiency conversion on forage						
Frame						
Longevity						
Consanguinity						
Fertility/Reproduction efficiency						
Calving ease/Unassisted calving						
Maternal quality						
Udder support						
Udder health & Udder quality[3]						
Milking speed						
Udder capacity						
Front teat placement						
Docility						
Parasite Load						
Parasite resistance/ TGI[4] parasites resistance						
Wellness (never see a vet)						
Heat tolerance						
Adaptation to grazing[5]						
GHG emissions						
Water use efficiency						
Future scenario						
Milky production						
Milk production consistency (despite feed quality)						
Crossbreeding (adapted x milk specialized)						
Milk fat production						
Milk protein production						
Milk fat percentage						
Milk protein percentage						

Somatic cell score						
Body condition score						
Improve fatty acids for better human nutrition						
Improve proteins for better human nutrition						
Frame/liveweight						
Longevity						
Feed conversion efficiency on forage						
Consanguinity						
Reproduction efficiency/Fertility						
Crossbreeding to improve reproduction (if needed)						
Calving ease/Unassisted calving						
Maternal quality						
Udder support						
Udder health & Udder quality[3]						
Milking speed						
Udder capacity						
Front teat placement						
Temperament						
Docility						
Parasite load						
Resistance to parasites/ Resistance to TGI parasites						
Resistance to blood borne disease						
Resistance to ticks						
Wellness (never see a vet)						
Resistance to heat stress						
Resilience/Resilient to external perturbations						
Adaptability to once-a-day milking						
Adaptation to grazing						
Efficiency of nitrogen utilisation						
GHG emissions						
Water use efficiency						

[1]Dairy 1 farm, Massey University, Palmerston North, New Zealand; ESL: Embrapa Southeast Livestock, Brazilian Agricultural Research Corporation - Embrapa, Sao Carlos, Brazil; INRAE-AM: INRAE ASTER-Mirecourt Research Farm (INRAE-AM, French Institute for Agricultural, Food and Environment Research - INRAE, Mirecourt, France; KRS, Kapiti Research Station, International Livestock Research Institute - ILRI, Nairobi, Keny; UWP-PF: UW-Platteville Pioneer Farm, University of Wisconsin – Platteville, Platteville, US.

[2]MIG: Managed intensive grazing; [3]Udder health index: improved mastitis resistance & clinical mastitis levels, decreased cell counts - Udder quality index: fore attachment, development, balance, support, teat gap, orientation/length/form of teats; [4]TGI: Gastrointestinal System; [5]Index: foot angles, hock morphology, resistance of the hooves, ease of locomotion.

File S4 – List of traits for beef cattle relevant to the research farms[1] in the current climate and in a future climate change scenario (increased global surface warming of 2 ºC by 2046-2065), and their prioritisation for selection (low priority – lightest square, high priority – darkest square, medium priority – intermediate colour square; blue for desired increases, red for desired decreases).

Traits & climate	ESL	KRS	INIA – PAP	INRAE – SLP	UCD-LTGP[2]	SRUC-KA	NWFP
Current climate							
Growth rate							
Yearling weight							
Crossbreeding (adapted x meat specialized)							
Carcass weight							
Carcass conformation							
Carcass bonus							
Carcass fat							
Out of spec weight							
Out of spec confirmation							
Meat quality (tenderness)							
Eye muscular area							
Rib fat							
Intramuscular fat							
Feed intake							
Maintenance requirements/Cow mature weight							
Moderate frame							
Feed efficiency/Feed efficiency on forage							
Cow's fertility/Reproduction efficiency							
Gestation length							
Scrotal size							
Birth weight							
Unassisted calving							
Calving difficulty							
Calf mortality							
Milk production							
Maternal quality/ability							
Docility							
Weaning weight							
Polledness							
Resistance to: deseases, parasites, TGI[3] parasites, worms							
Animal health							
Heat tolerance							
Water use efficiency							
Future scenario							
Growth rate							
Crossbreeding (adapted x meat specialized)							
Carcass weight							
Carcass conformation							
Carcass bonus							

Carcass fat							
Out of spec weight							
Out of spec confirmation							
Meat and carcass quality							
Feed intake							
Frame size							
Maintenance requirements/Cow mature weight							
Moderate frame size							
Feed efficiency/Feed efficiency on forage							
Longevity							
Fertility/Reproduction efficiency							
Gestation length							
Unassisted calving							
Birth weight							
Milk production							
Maternal quality/ability							
Calving difficulty							
Calf mortality							
Docility/Easy to manage							
Polledness							
Resistance to: deseases, parasites, TGI parasites, worms							
Resilient to external perturbations							
Hardiness							
Heat tolerance/resistance							
Ability to digest low-quality forages							
Water use efficiency							
Environmental footprint/GHG emissions							

[1]ESL: Embrapa Southeast Livestock, Brazilian Agricultural Research Corporation - Embrapa, Sao Carlos, Brazil; INIA-PAP: INIA Palo a Pique, National Institute of Agricultural Research - INIA, Treinta y Tres, Uruguay; INRAE-SLP: INRAE Saint Laurent de la Prée Research Farm, INRAE, Saint-Laurent-de-la-Prée, France; KRS, Kapiti Research Station, International Livestock Research Institute - ILRI, Nairobi, Kenya; NWFP: North Wyke Farm Platform, Rothamsted Research – North Wyke, Okehampton, UK; SRUC-KA: Kirkton & Auchtertyre upland research farms, Scotland's Rural College - SRUC, Crianlarich, UK; UCD-LTGP: Lyons Farm Long-term Grazing Platform, University College Dublin - UCD, Dublin, Ireland.

[2]Dairy calf to beef

[3]TGI: Gastrointestinal System

File S5 – List of traits for sheep relevant to the research farms[1] in the current climate and in a future climate change scenario (increased global surface warming of 2 °C by 2046-2065), and their prioritisation for selection (low priority – lightest square, high priority – darkest square, medium priority – intermediate colour square; blue for desired increases, red for desired decreases).

Traits & climate	KRS[2]	SRUC-KA	NWFP	UWA-FF	HRC
Current climate					
Growth rate		High (blue)	High (blue)		
Lamb' days to finishing					High (red)
Lamb kill-out weight/Carcass weight			Medium (blue)		High (blue)
Carcass fat		Low (red)			
Carcass muscle		Low (blue)			
Carcass quality (premium class)			Medium (blue)		
Wool quality				Low (blue)	
Ewe mature weight		Medium (red)			
Feed efficiency on forage	High (blue)		High (blue)		
Fertility/Reproduction	High (blue)			High (blue)	
Number/percentage of lambs reared		High (blue)	Medium (blue)		High (blue)
Unassisted lambing	Medium (blue)				
kg lamb weaned/ewe liveweight (%)					High (blue)
Maternal ability	High (blue)	High (blue)	Medium (blue)		
Resistance to: worms, TGI[3] parasites	High (blue)			High (blue)	
Resistance to flystrike				High (blue)	
Methane emissions	Medium (blue)			Medium (red)	
Future scenario					
Growth rate		High (blue)	Medium (blue)		
Lamb' days to finishing					High (red)
Lamb kill-out weight					High (blue)
Carcass fat		Medium (red)			
Carcass muscle		Medium (blue)			
Carcass quality			Low (blue)		
Wool quality				Low (blue)	
Ewe mature weight		High (red)	High (red)		
Feed efficiency/Feed efficiency on forage	High (blue)	Medium (blue)	High (blue)	Medium (blue)	
Longevity		High (blue)			
Fertility/Reproduction	High (blue)			High (blue)	
Number of lambs reared (optimal)/Percentage lambs reared		High (blue)	Medium (blue)		High (blue)
Early lambing – early finishing			Medium (blue)		
Outdoor lambing (lambing ease)			High (blue)		
Unassisted lambing	Low (blue)				
Maternal ability	Medium (blue)	High (blue)	High (blue)		
kg lamb weaned/ewe liveweight (%)					High (blue)
Foot-rot resistance		Medium (blue)			Medium (blue)
Resistance to: parasites, TGI parasites, worms	High (blue)	High (blue)		High (blue)	High (blue)
Fluke resistance					High (blue)
Heat tolerance/Adapted to high temperatures	High (blue)		High (blue)	Low (blue)	High (blue)
Climatic resilience		Medium (blue)		High (blue)	

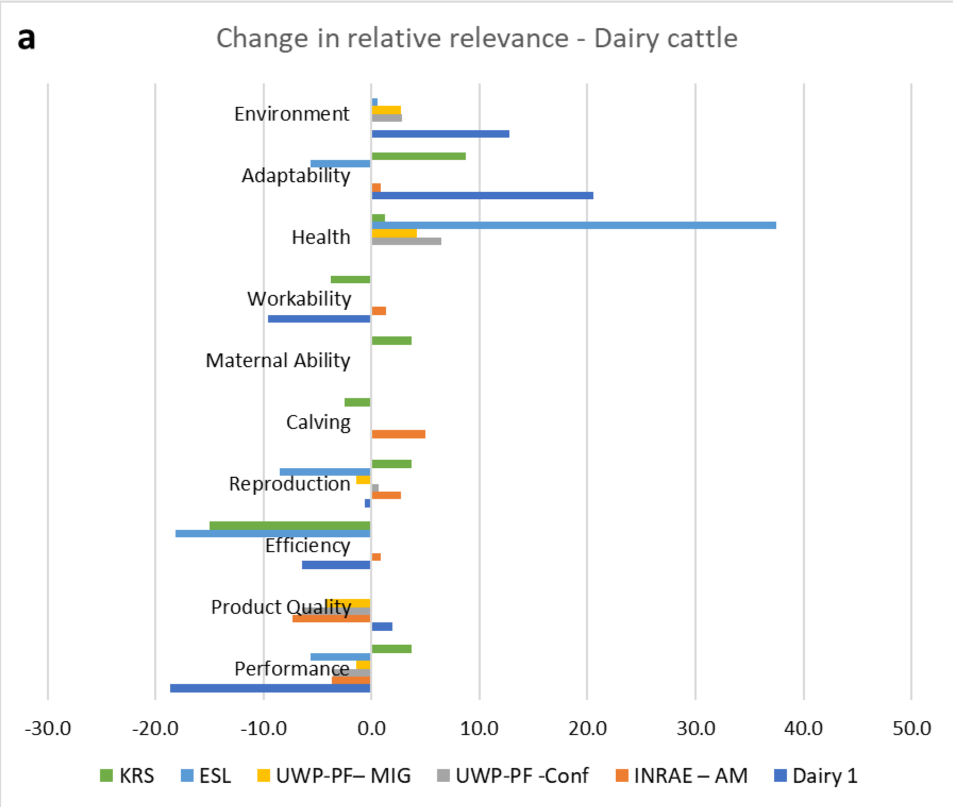
Robustness or Versatility					
Wool shedding					
GHG emissions/Methane emissions					

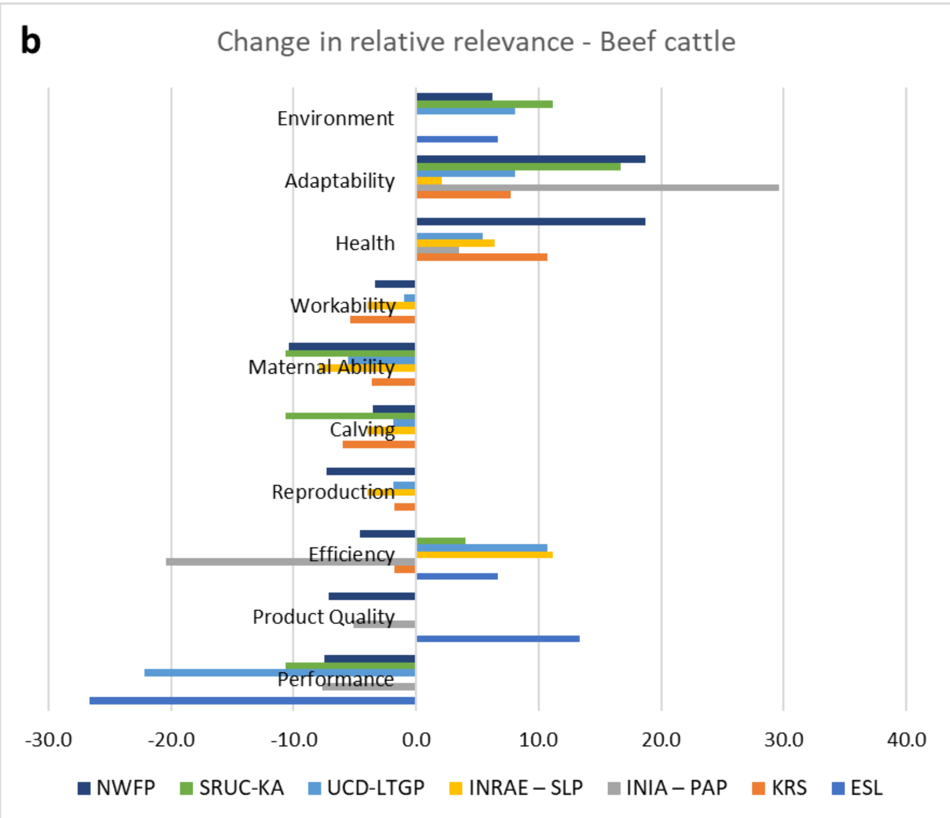
[1]HRC: Henfaes Research Centre, Bangor University, Bangor, UK; KRS, Kapiti Research Station, International Livestock Research Institute - ILRI, Nairobi, Kenya; NWFP: North Wyke Farm Platform, Rothamsted Research – North Wyke, Okehampton, UK; SRUC-KA: Kirkton & Auchtertyre upland research farms, Scotland's Rural College - SRUC, Crianlarich, UK; UWA-FF: UWA Future Farm 2050, University of Western Australia - UWA, West Pingelly, Australia.

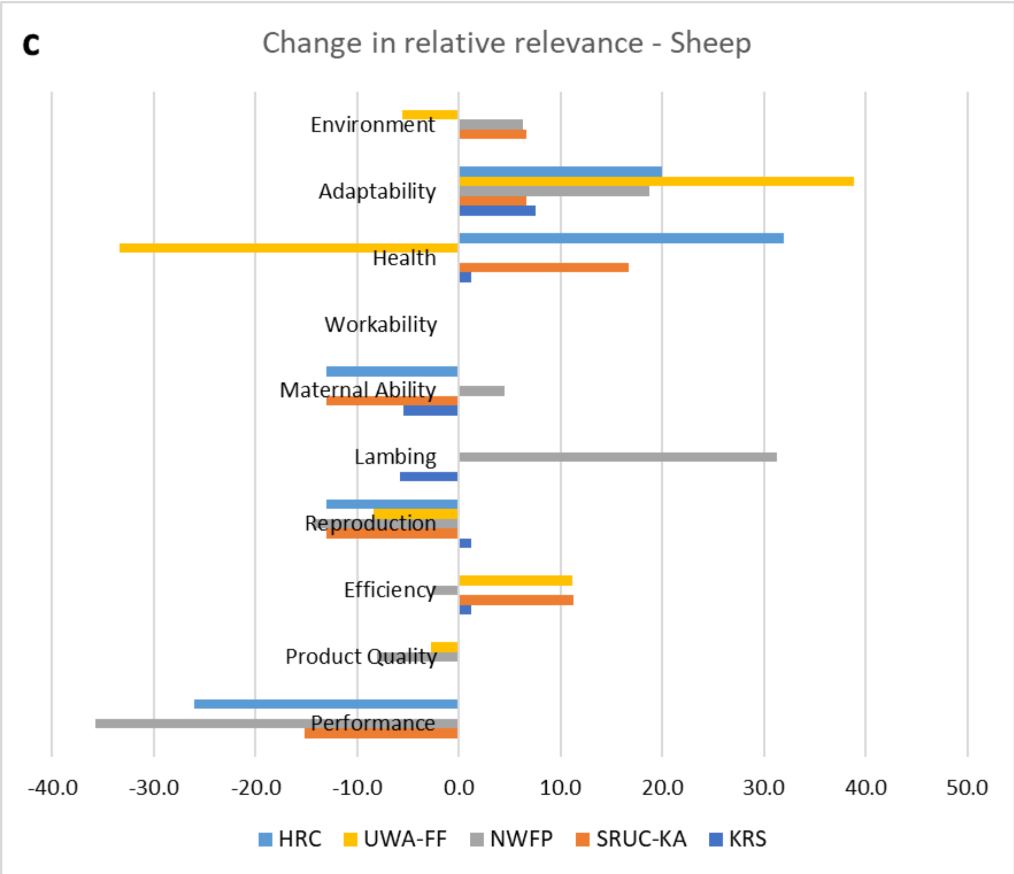
[2]Includes goats

[3]TGI: Gastrointestinal System

File S6 – Changes in relative relevance of traits categories dairy (a) beef cattle (b) and sheep (c) within the different research farms from the current climate (inner circle) to a future climate change scenario (outer circle; increased global surface warming of 2 oC by 2046-2065).







Individual traits within each of the 10 categories were ranked as low, medium and high priority, and a value of 1, 2 or 3 points were assigned, respectively. The sum of points for each category was expressed as a percentage of the total points for each research farm. The difference in relative relevance for each category of traits was calculated as its percentage in the future climate minus its percentage in the current climate.

Dairy 1 farm, Massey University, Palmerston North, New Zealand; ESL: Embrapa Southeast Livestock, Brazilian Agricultural Research Corporation - Embrapa, Sao Carlos, Brazil; INRAE-AM: INRAE ASTER-Mirecourt Research Farm (INRAE-AM, French Institute for Agricultural, Food and Environment Research - INRAE, Mirecourt, France; KRS, Kapiti Research Station, International Livestock Research Institute - ILRI, Nairobi, Keny; UWP-PF: UW-Platteville Pioneer Farm, University of Wisconsin – Platteville, Platteville, US.; MIG: Managed intensive grazing; Conf: Confined; INIA-PAP:INIA Palo a Pique, National Institute of Agricultural Research - INIA, Treinta y Tres, Uruguay; INRAE-SLP: INRAE Saint Laurent de la Prée Research Farm, INRAE, Saint-Laurent-de-la-Prée, France; NWFP: North Wyke Farm Platform, Rothamsted Research – North Wyke, Okehampton, UK; SRUC-KA: Kirkton & Auchtertyre upland research farms, Scotland's Rural College - SRUC, Crianlarich, UK; UCD-LTGP: Lyons Farm Long-term Grazing Platform, University College Dublin - UCD, Dublin, Ireland. HRC: Henfaes Research Centre, Bangor University, Bangor, UK; UWA-FF: UWA Future Farm 2050, University of Western Australia - UWA, West Pingelly, Australia.