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Reflections

Animal science Down Under: a history of research, development and extension in support of Australia's livestock industries

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Abstract. This account of the development and achievements of the animal sciences in Australia is prefaced by a brief history of the livestock industries from 1788 to the present. During the 19th century, progress in industry development was due more to the experience and ingenuity of producers than to the application of scientific principles; the end of the century also saw the establishment of departments of agriculture and agricultural colleges in all Australian colonies (later states). Between the two world wars, the Council for Scientific and Industrial Research was established, including well supported Divisions of Animal Nutrition and Animal Health, and there was significant growth in research and extension capability in the state departments. However, the research capacity of the recently established university Faculties of Agriculture and Veterinary Science was limited by lack of funding and opportunity to offer postgraduate research training. The three decades after 1945 were marked by strong political support for agricultural research, development and extension, visionary scientific leadership, and major growth in research institutions and achievements, partly driven by increased university funding and enrolment of postgraduate students. State-supported extension services for livestock producers peaked during the 1970s. The final decades of the 20th century featured uncertain commodity markets and changing public attitudes to livestock production. There were also important Federal Government initiatives to stabilise industry and government funding of agricultural research, development and extension via the Research and Development Corporations, and to promote efficient use of these resources through creation of the Cooperative Research Centres program. These initiatives led to some outstanding research outcomes for most of the livestock sectors, which continued during the early decades of the 21st century, including the advent of genomic selection for genetic improvement of production and health traits, and greatly increased attention to public interest issues, particularly animal welfare and environmental protection. The new century has also seen development and application of the 'One Health' concept to protect livestock, humans and the environment from exotic infectious diseases, and an accelerating trend towards privatisation of extension services. Finally, industry challenges and opportunities are briefly discussed, emphasising those amenable to research, development and extension solutions.

Additional keywords: behaviour, genetics, health sciences, meat science, nutrition, reproduction.

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Introduction

Australia's livestock industries were established over 200 years ago in a diverse range of environments that mostly were totally unfamiliar to immigrant farmers and graziers. Much of the subsequent success of the nascent industries in overcoming these environmental and other challenges can be attributed to a scientific community that long has been considered to punch well above its weight in international circles. This is particularly the case for the pastoral industries, where wool, beef, sheep meat and dairy production have easily satisfied the domestic demands of a growing and increasingly affluent population and, to varying degrees, have developed lucrative export markets. Although relatively smaller in global terms, the more intensive pig and poultry industries have also benefited greatly from internationally competitive research and development by Australian scientists.

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This article tells the story of people and institutions that have contributed scientifically to the productivity and economic success of the Australian livestock industries. It deals not only with the often-stellar scientific achievements of individuals and research groups, but also with visionary leadership that set the scene for these achievements. Missed opportunities are also discussed, including the reluctance of academic institutions to embrace greater responsibility for the translation of scientific discovery into industry adoption and application. In conclusion, some of the present and likely future challenges facing the Australian industries are identified, especially those that appear to be amenable to scientific solutions.

Finally, this must be considered a relatively brief, selective history that, by specifying certain individuals, institutions, events and achievements, runs a risk of important omissions. For these the author apologises in advance.

A brief history of the Australian livestock industries

In this section, a brief description will be given of the patterns of development of the major Australian livestock industries from 1788 to the present, with reference to key events, to provide historical background and context to the achievements of Australia's animal science community, as discussed in the rest of this article. The author has drawn heavily on several excellent sources, which should be consulted for more detailed and comprehensive accounts of the history of animal agriculture in Australia (Peel 1986; Parsonson 1998; Henzell 2007). In particular, the book by Henzell (2007) includes informative graphical representation of the patterns of growth in animal numbers and production volume during the 230 years since the arrival of the First Fleet.

Initiation and early distribution

The First Fleet arrived at Botany Bay on 24 January 1788 with several hundred livestock. Most were chickens and other species of poultry, but concurring sources also list as many as seven cattle, 44 sheep, 19 goats and 32 pigs, most of which were purchased at the Cape of Good Hope while *en route* from England (Parsonson 1998; Timbury 2013*a*). The Cape native (part Zebu) cattle and fat-tailed sheep would not have a significant influence on the subsequent genetic development of the cattle and sheep industries in the new colony. Early experiences with these species were inauspicious, as all but one of the cattle escaped in June 1788 (Stockdale 1789; Timbury 2013*b*), and by the end of the year, only one sheep had not been eaten or died of other causes. The fates of the other livestock species are uncertain, although Parsonson (1998) cites first-hand evidence that the pigs, goats and poultry 'thrived' in their new home.

The sheep flock was soon replenished by further imports of Bengal and Cape fat-tailed breeds, as well as some British breeds. These animals were prolific, such that numbers had risen to 6000 by 1800 and to 32 000 by 1810. The first Spanish Merinos arrived in 1797, some of which were purchased by Samuel Marsden and John Macarthur, who were to become pioneers of the Australian wool industry (Garran and White 1985). Also in 1797, over 200 'wild' cattle were discovered across the Nepean River in an area near modern Camden, to be named 'Cowpastures' (Parsonson 1998; Timbury 2013*b*). This herd of escapees and their progeny continued to grow substantially under the protection of Governor Hunter, who ordered Cowpastures to be reserved for this purpose, demonstrating the potential for future development of the cattle industry, and presaging the adaptability and resilience of *Bos indicus* genotypes in the Australian pastoral environment.

Subsequent early importation of cattle, sheep and other livestock to Sydney, and the later spread of pastoralism to the rest of New South Wales (NSW), including the Port Phillip District and Queensland, and to the other colonies, are comprehensively documented by Parsonson (1998). Thus, pastoral runs were established in the central and western regions of present-day NSW soon after the Blue Mountains were crossed in 1813, while the first sheep and/or cattle and other livestock were shipped to Van Diemen's Land, the Swan River Colony, the Port Phillip District and South Australia in 1803, 1829, 1834 and 1837 respectively. In the late 1830s and early 1840s, the first overland drives out of present-day NSW reached the Port Phillip District, South Australia and southern Queensland. As a result, by 1860, Australia had total populations of >15 million sheep and 4 million cattle distributed across much of the present-day pastoral zone, except for far north Queensland, the Northern Territory and north-west Western Australia (Henzell 2007).

Wool and sheep meat production

The new colony's potential for wool production was recognised early in the 19th century by John and Elizabeth Macarthur, Samuel Marsden, and Governor King. Through the importing of Spanish Merinos and selective breeding, the number and quality of wool sheep grew quickly, such that by the 1830s, wool was Australia's most valuable export, much of which was consumed by England's burgeoning textile industry (Garran and White 1985; Henzell 2007). During the rest of the 19th century, the industry continued to grow, such that by 1890, the national flock totalled 100 million. Merino productivity was enhanced during the 1860s and 1870s by the breeding efforts of the Peppin brothers in the Riverina to create the prototype of the Australian Merino – a large-framed, plain-bodied sheep with long, soft, fine fleece (Clune 1965; Massy 2007). It was hampered by the introduction of highly wrinkled Vermont Merinos, as well as by diseases, such as scab, footrot, catarrh and flystrike (Parsonson 1998). However, it took a combination of major drought and economic depression in the 1890s to curtail the steady rise in sheep numbers and wool production up to that time (Henzell 2007).

Wool production and exports resumed steady growth during the first half of the 20th century, partly interrupted by the Great Depression and influenced by two world wars. Profitability of the industry peaked during the early 1950s, stimulated by demand due to the Korean War. Since then, the value of wool exports to the nation and to individual producers has mostly been in serious decline, due to competition from synthetic fibres and a resurgent cotton industry. This long-term pattern was not helped by the Federal Government's introduction of a reserve price scheme for wool in 1974 that was intended to deal with the overproduction and price collapse in the early 1970s. Although the industry experienced a brief rally during the late 1980s, the scheme ultimately failed and was terminated in 1991 (Massy 2011).

Subsequent depression of prices led to a major decline in the national flock from a peak of almost 180 million in 1970 to a nadir of less than 70 million in 2015–16, and to a restructuring of the industry away from wool in favour of meat production. However, during the 2 years before the time of writing, the wool industry, especially its fine wool sector, has been enjoying prices not seen in many decades. This has been driven by strong demand from China and other importers, and a sluggish response in supply related to Australia's greatly diminished flock of wool sheep. The industry's focus on marketing wool as a luxury product rather than a staple commodity also may have helped.

During most of the 19th century, wool – rather than meat production – was the clear priority of people involved in the sheep industry, and almost all meat was consumed domestically as mutton. This changed somewhat after the advent of refrigeration in the 1880s, and during that decade Australia shipped seven times as much frozen mutton as beef to the United Kingdom (UK) (Critchell and Raymond 1912). However, British consumers were less than enthusiastic about Merino mutton, much of which remained in Australia; even so, domestic consumption of mutton lagged behind that of beef, and continued to do so during most of the next century (Henzell 2007). The sheep meat industry began to change in the early 1990s as it responded to market research showing a potential for growth in sales of larger, leaner and more uniform lamb carcasses in both export and domestic markets. As discussed in a later section, this response was greatly assisted by research-driven advances in genetics, nutrition and meat processing technology. Thus, even with the recent spike in wool prices, the value of the Australian sheep meat (predominantly lamb) industry now exceeds that of the wool industry.

Since the 1960s, Australia has also had a substantial live export trade in sheep, initiated in Western Australia and mostly serving Middle Eastern markets. These shipments peaked at ~7.3 million head in 1983, but had declined to ~1.8 million head in 2017–18 (Meat & Livestock Australia 2018*a*). Since the latter figures were published, live exports of sheep to the Middle East have plummeted due to cessation of shipping operations during the northern hemisphere summer. However, approximately half of this reduction was offset by increased export of chilled carcasses to the Middle East (Meat & Livestock Australia 2018*b*), which is an encouraging trend.

Beef production

The earliest cattle in Australia were used mostly for draught purposes, with meat and milk being desirable co-products. Although bullock power remained important throughout the 19th century, this priority soon changed as improved British meat breeds were imported and cattle numbers increased rapidly with the establishment of new pastoral runs ever further from Sydney. Thus, by 1830, NSW was self-sufficient in beef and was exporting salted product to the other colonies. However, even after the introduction of refrigeration, relatively little Australian beef was exported overseas to the UK or elsewhere during the late 19th and early 20th centuries (Henzell 2007). During this period, Australians did their best to take up the slack, consuming over 60 kg of beef per person per year in the 1890s (Coghlan 1904), and almost as much even during the depression years of the 1930s.

This largely domestic focus changed during the 1950s with the opening of the United States of America (USA) market for ground (hamburger) beef, and later, for more valuable cuts in Japan and other east Asian countries. As a result, beef cattle numbers and production increased steadily during the next half-century, with a spectacular spike during the 1970s that was stimulated by unsustainably high prices and problems in the wool and dairy industries (Henzell 2007). Despite continuing market volatility and a major drought during the first decade of the 21st century, beef production remains one of Australia's most important agricultural industries and export earners, as recently documented by Greenwood *et al*. (2018). Thus, in 2016–17, the industry's 25 million cattle produced 2.1 million tonnes of beef and veal carcasses, 68% of which was exported to 77 countries, principally Japan, the USA, Korea and China. In addition, >820 000 head of live beef cattle were exported to Indonesia, Vietnam, China and several other countries, mostly from herds in north Queensland and the Northern Territory. Much of the Australian industry continues to be pasture-based, but in recent decades there has been a trend towards feedlot finishing to meet market specifications, with 39% of adult cattle slaughtered in 2016–17 finished on grain-based diets (Greenwood *et al*. 2018).

Although almost all of the common British breeds of cattle were represented from the earliest decades of the new colony, by the end of the 19th century the Shorthorn breed was predominant, especially in the tropical and subtropical north. Subsequently, the Aberdeen Angus and Hereford breeds came to dominate the temperate southern regions and, during the 1950s, the introduction of American Brahman cattle revolutionised the northern industry (Parsonson 1998). These *B. indicus* cattle continue to be the foundation of northern beef production because of their heat tolerance, tick resistance and foraging abilities, although there is continuing development of so-called 'tropical composite' breeds that seek to take advantage of combining the adaptability of *B. indicus* with the productivity of *B. taurus* genotypes.

No history of the Australian beef industry would be complete without reference to the devastating impact of diseases, such as pleuropneumonia and tuberculosis. Industry experiences with these and other important bovine diseases have been amply documented by Parsonson (1998), and the scientific background to their national eradication in 1973 and 1997 respectively is discussed in later sections.

Dairy production

The Australian dairy industry was much slower to develop than the more extensive wool and beef industries, hampered by the poor quality of native pastures, and the inability to store milk and its products. Nevertheless, NSW (including present-day Victoria) was self-sufficient in butter by the 1830s, although the Australian colonies were net importers of cheese throughout the 19th century (Henzell 2007). Gradually, specialist dairying areas were established, first in the Illawarra region south of Sydney and later in other, more favoured parts of NSW and the new colony of Victoria. The industry grew rapidly between 1860 and 1890 when the national herd was estimated to number ~950 000 cows, 80% of which were in NSW and Victoria. This period also marked the advent and growth of refrigerated butter exports to the UK.

The industry then grew steadily until ~1970, punctuated by some declines during the two world wars. During this period, Australia continued to export approximately half of its growing supply of butter and increasing amounts of other manufactured products, mostly to the UK. As clearly documented by Henzell (2007), most of the growth before 1950 was due to increasing cow numbers, whereas subsequent increases in national production have been due to increased yield per cow (see below).

Major restructuring of the Australian dairy industry was initiated by its exclusion from the British market following the UK's entry into the European Economic Community (EEC) in 1973. This greatly accelerated departures from the industry by producers in northern NSW, Queensland and south-west Western Australia, many of whom had been struggling to be profitable for decades. Soon afterwards, the complex scheme of government subsidy and price supports began to be wound back, with pooling of returns from domestic and exported products ceasing in 1986. Finally, deregulation of the markets for both manufactured products and liquid milk was completed in 2000, leaving Australia with possibly the most unregulated and unprotected dairy industry in the world (Edwards 2003). The net outcome was an industry with fewer, more productive cows, mostly located on larger farms in Victoria and southern NSW. Thus, between 1960 and 2017, the national herd decreased by 53%, the number of dairy farms declined by 90%, yet the total volume of milk produced increased by 40% due to a 300% increase in milk yield per cow (Table 1). The scientific bases for this astonishing increase in productivity will be discussed in later sections.

Pig and poultry production

As noted earlier, pigs and poultry were well represented among the livestock that arrived with the First Fleet. However, for much of the subsequent couple of centuries, the pig industry remained a sideline enterprise on dairy or grain farms, while the production of eggs and poultry meat was largely the province of domestic households. In both cases, these industry structures were to change radically during the second half of the 20th century, evolving to become significant, intensively managed industries in their own right.

Pig production was tied to dairying because, until the 1950s, skim milk was an otherwise useless by-product of butter making, but an excellent source of energy and protein for pigs. Dairy farms close to cheese factories also used the by-product whey for pig feed (Dunkin 1985). In addition, pigs were kept by grain farmers to augment cash flow throughout the year, and to utilise surplus grain and cereal by-products. These sideline enterprises were numerous, but individually small, with ~50 000 producers having an average herd size of 4.3 sows in 1960 (Dowling 2006). Progressive deregulation of the dairy industry from the 1970s reduced the number and geographic distribution of dairy farms (see above), while on-farm refrigeration and improved processing technologies greatly decreased the availability of skim milk.

Table 1. Comparison of Australian dairy industry structure and performance in 1959–60 and 2016–17

Parameter	1959–60	2016–17
No. of cows (millions)	3.24	1.51
No. of farms	64 200	5789
Average herd size	51	261
Total milk production (million L)	6392	9015
Milk per cow (L)	1959	5819

The advent of the intensification of the Australian pig industry was marked by establishment of the Mayfair Group's farrow-to-finish operation near Bendigo, Victoria, in 1965, which by 1970 had grown to 2000 sows. Other similar enterprises soon followed, including the 1200 sow Wonga pig farm at Young, NSW, in 1968, and another Mayfair enterprise at Menangle, NSW, in 1971. Notably, the units at Bendigo and Young were led by Drs Dudley Smith and John Holder respectively, both of whom were accomplished nutritionists and familiar with the principles of disease control in large herds (Cutler and Holyoake 2007). This radical change in production system was associated with a progressive decline in the number of pig enterprises to ~20 000 in 1980 and only ~2500 in 2000. After almost doubling during the 1970s, the national sow herd has remained relatively static at 300 000 to 350 000 since 1980. However, the annual production of pig meat has increased from ~200 000 tonnes in 1980 to almost 400 000 tonnes in 2016–17 due to improved production efficiency and increased slaughter weights (Dowling 2006). Despite its internationally competitive levels of performance, in recent decades the Australian pig industry has been challenged by the introduction of imported frozen product from North America and Europe, major variations in feed costs, and often negative international terms of trade.

Historically, small numbers of chickens were kept by householders mainly to produce eggs, with meat being a co-product based on surplus roosters and culled hens. As the Australian population became urbanised during the first half of the 20th century, the egg industry developed mostly adjacent to cities and towns, and progressively intensified from free-range to barn and cage layer systems (Scott *et al*. 2009). Later development featured geographic shifts to cereal cropping regions; aggregation of small- to medium-sized enterprises to relatively few, very large production units mostly situated in NSW, Queensland and Victoria; and major improvements in genetics, nutrition, health management and biosecurity. Some of this reconstruction was facilitated by the abolition of state government egg quotas in the 1990s. Also, the rate of genetic progress was enhanced by the establishment of the Torrens Island quarantine station in 1987, which allowed importation of genetically superior eggs and birds from overseas sources. In 2017–18, ~22 million laying hens produced 516 million dozen eggs, the great majority of which were used for domestic consumption (Australian Eggs 2018). Less than 50% of this production was by caged layers, and over 40% was in free-range systems, responding to a marked shift in consumer preference during the past decade.

As the Australian egg industry specialised and grew, so too did the chicken meat (broiler) industry. Although official records were not kept until the mid-1960s, industry sources estimate that

~3 million broilers were produced in 1950–51, compared with ~664 million in 2017–18 (Australian Chicken Meat Federation 2018). The rate of increase in productivity over this period has been astonishing. For example, in 1975, it took 64 days and required 5.0 kg of feed for a broiler chick to reach a slaughter weight of 2 kg; in 2018, the time from hatch to slaughter had more than halved to 30 days and required a mere 3.5 kg of feed (Australian Chicken Meat Federation 2018). The consequent decrease in price per unit of product, together with its consistency and other appealing attributes, has led to an increase in annual Australian consumption of chicken meat from 4.4 kg per person in 1962 to over 43 kg in 2011 (Wong *et al*. 2015).

Today, the broiler industry is Australia's most consolidated and integrated livestock industry, with only two companies, Baiada and Inghams, accounting for 70% of total sales, and another five contributing a further 25%. Meat production enterprises are segregated into breeder farms that produce fertile eggs, hatcheries that produce day-old chicks, grower farms that grow the chicks to slaughter, and processing plants that slaughter and prepare whole chickens and chicken parts for retail sale, mostly to supermarkets. As in the egg industry, grower enterprises are being pushed by consumer sentiment to adopt free-range systems, with more than 15% of the industry producing 'free-range' broilers in 2015 (Scott *et al*. 2017).

The 19th century – producer innovation and the rise of agricultural institutions

Survival of the First Fleet settlement at Sydney Cove was threatened by a lack of agricultural skills and a challenging physical environment. Governor Phillip's concern about the capacity of the new colony to support itself led to his sponsorship of James Ruse, a convicted burglar who had gained substantial farming experience in his native Cornwall, to demonstrate self-sufficiency for himself and his family on a few acres near present-day Parramatta. While grain growing rather than livestock production was to be Ruse's priority, it is notable that, in addition to cleared land, he was provided with two sows and six hens. His success in the early 1790s was rewarded by the grant of 30 acres, which became known as the 'Experiment Farm', now an historic site managed by the National Trust (National Trust of Australia (New South Wales) 1976). This name is perhaps misleading, in that the farm was not used for controlled experimentation as we now understand it, but it does indicate an early appreciation of the need for agricultural innovation in the new colony.

Producer innovation

In the northern hemisphere, there were major advances during the late 18th and 19th centuries in understanding of principles that underpin the animal and veterinary sciences (Russell 1966). Thus, the English farmer, Robert Bakewell, generally is regarded as the father of livestock breeding for his work during the latter part of the 18th century on selection for desirable production traits in sheep and cattle (Wykes 2004). The chemical and physiological bases of animal nutrition were also emerging from systematic investigations by scientists, such as Lavoisier, Zuntz and Rubner in Europe, and Armsby in the USA. The microbiological causes of infectious disease in animals, including humans, were established by Pasteur during the 1860s. However, it is evident that most of the major progress in breeding, husbandry and disease prevention in Australian livestock before 1900 was due to the ingenuity, persistence and commercial ambition of producers rather than the formal application of scientific principles established in the northern hemisphere.

By far the most impressive example of genetic improvement was that in wool production and environmental adaptability of Merino sheep. Although John Macarthur has been touted as the father of the Australian wool industry and Merino breeding, re-evaluation of his contributions suggests that his undoubted talents for self-promotion and acquisition of resources greatly exceeded his abilities in sheep breeding and husbandry (Clune 1965; Garran and White 1985; Massy 2007). These authors consider Governor King and Samuel Marsden to have made more important contributions to the early genetic improvement of wool sheep in the new colony. However, neither they nor the Macarthurs were to make significant contributions to the development of the modern Australian Merino. In contrast, in just over a decade from the late 1850s, the Peppin family at Wanganella near Deniliquin, NSW, was to have an indelible influence on Merino breeding that persists to the present day. Their success was based on a combination of judicious cross-breeding of Merinos with longer-woolled breeds, such as the Leicester, and skilful evaluation of and selection for wool production and quality. Much of the latter success has been attributed to a famous wool classer, Thomas Shaw, who insisted on selecting animals that were adapted to the environment in which they were expected to produce (Garran and White 1985; Massy 2007).

It seems unlikely that 19th century Australian sheep and cattle graziers were aware of, let alone attempted to implement, even rudimentary principles of animal nutrition on their large, extensively managed pastoral runs where nutrient supply was solely dependent on the availability of native pasture. For example, the role and importance of microbial fermentation of feedstuffs in the rumen was not inferred by Zuntz until 1879 (Hungate 1966), and as late as 1876, an authoritative text on cattle management and diseases stated that the biological role of the rumen was feed storage and 'maceration' (Youatt 1876). Nevertheless, by trial and error, innovative graziers came to appreciate the variable quality and carrying capacity of native grasses, and adapted their pastoral management accordingly. Early attempts to introduce improved pasture species and the use of superphosphate fertiliser, especially in southern Australia, have been reviewed by Reed (2014). Notable among these efforts was the discovery in 1889 and later advocacy of an introduced volunteer species, subterranean clover (*Trifolium subterraneum*), by Amos Howard.

Among the numerous, poorly understood diseases that blighted the 19th century pastoral industries, perhaps the most damaging was sheep scab, caused by the *Psoroptes ovis* mite. The associated financial loss, mostly due to decreased wool production, to the colony of Victoria alone was estimated in 1865 to be over £500 000 (approximately $55 million in contemporary value). This led to two streams of innovation in the Australian pastoral sector: one technical, in the form of new and more effective acaricides and sheep dipping methods; the other organisational, in the form of the first Australian legislation aimed at controlling an animal disease. The latter, initially enacted in NSW in 1832, and gradually strengthened into the 1860s, eventually led to eradication of the disease from the Australian continent in 1896 (Stewart 1945).

Early agricultural institutions

The period from ~1870 to 1914 was marked by the founding of state departments of agriculture to solve practical problems in crop and livestock production and health, and extend the knowledge so gained to producers, and of agricultural colleges for vocational training of prospective farmers and graziers (Table 2). The motivation for these initiatives has been ascribed more to political concerns for the 'public interest' than to demands from the production industry, not discounting the fact that, as rural landlords, colonial governments had a direct fiscal interest in maintaining the private profitability of agriculture (McLean 1982). This author further suggested that the lack of 'push' from the farming sector was due partly to its preoccupation with land rights during the period in question, and partly to widespread ignorance of the possible benefits of research and technological development.

In all colonies (later states), the agricultural colleges were established mostly as initiatives of, and were administered by, the newly founded and publicly funded state departments of agriculture. This linkage would appear to have offered a golden opportunity to integrate agricultural education, applied research and extension, along the lines of the Land Grant System in the USA. Although aware of the early successes of the American System, those in power opted to emulate the so-called European System, which separated institutions responsible for applied research and extension from those responsible for more fundamental research and education (Falvey and Bardsley 1997), presumably because of greater familiarity based on personal experience. Some of the negative consequences of this decision are discussed in later sections.

The early research programs of the state departments were mostly carried out on regionally distributed experimental farms with a focus on improving broad-acre crop and horticultural production. Similarly, the curricula of the colleges were concerned more with cropping, horticulture and intensive animal husbandry than with pastoral management of sheep and cattle, notwithstanding the economic importance of their products, especially wool. Livestock activities in the new departments mostly dealt with identification and regulation of infectious diseases, incorporating the role of the Stock Branches created earlier in the latter half of the 19th century. Consequently, it is difficult to identify livestock research achievements by state employees before World War I that are remotely comparable to those of William Farrer, the NSW Department's famous wheat breeder (Mylrea 1990). Nevertheless, such agronomic successes offered livestock producers an example of the benefits of publicly funded agricultural research. Also, the colleges, although never attended by more than a small fraction of would-be farmers, gradually lifted the technical skills and appreciation for innovation within their client industries.

Between the wars: development of research, development and extension capacity in the universities, Council for Scientific and Industrial Research and state departments

The universities

Between the decade preceding World War I and the onset of World War II, Faculties of Agriculture were created at the Universities of Melbourne (1905), Sydney (1910), Adelaide (1927), Queensland (1927) and Western Australia (1936). Often, however, the first academic appointments and student enrolments in these units did not occur until years afterwards, while in the interim, teaching of agricultural subjects sometimes was provided by one or two members of other academic units. For example, Thomas Cherry was not appointed as the first Dean of Agriculture at Melbourne until 1912, 7 years after foundation of the Faculty, and in Queensland, the Deanship was not filled for 20 years until the appointment of Hartley Teakle in 1947! Certainly, external circumstances, including World War I and the Great Depression, contributed to slow development of the new Faculties of Agriculture. Also, it is likely that some university leaders considered the teaching of agriculture to be the province of the state-operated colleges, and not of sufficient academic rigour to be included in their curricula. In the two oldest universities, this attitude was gradually overcome by the exceptional, long-term leadership of Robert Dickie Watt, the

Table 2. Foundation of Departments of Agriculture and early agricultural colleges in Australian colonies and states

Colony/state	Department	Year	College	Year
New South Wales	Agriculture[A]	1890	Hawkesbury	1891
Victoria	Agriculture[B]	1872	Dookie	1886
			Longerenong	1889
			Burnley	1891
Queensland	Agriculture	1887	Gatton	1897
South Australia	Bureau of Agriculture[C]	1888	Roseworthy	1883
Western Australia	Bureau of Agriculture[D]	1894	Muresk	1926
Tasmania	Agriculture	1911	Unnamed[E]	1915

[A]Branch of the Department of Mines until made autonomous in 1907.
[B]Branch of the Department of Crown Lands and Survey until made autonomous in 1890.
[C]Became Department of Agriculture in 1902.
[D]Became Department of Agriculture in 1898.
[E]Short-lived venture.

foundation Dean at Sydney from 1910 to 1946 (Yeates 1987) and Samuel Wadham, Dean at Melbourne from 1927 to 1956 (Falvey and Bardsley 1997). These men, both of British origin, did much to raise the profile of agricultural science within their institutions and beyond, and to provide service to the farming communities of NSW and Victoria, for which each was knighted.

However, during these early decades, a lack of qualified staff and external funding from government or private sources greatly limited the scope and depth of agricultural research by the universities (Wadham 1951). A notable exception was the creation of the Waite Institute at the University of Adelaide in 1924, made possible by a large bequest from a leading grazier, Peter Waite. The opportunity to train future generations of research scientists was also curtailed by a lack of provision for postgraduate training in Australian universities. It is revealing to note that the first scientific publication of the University of Western Australia was Eric Underwood's undergraduate honours thesis on the botanical and chemical composition of pasture (Underwood 1929; Blaxter 1981). As discussed later, Underwood would go on to become one of Australia's most illustrious animal scientists during his career with the Western Australian Department of Agriculture and the University of Western Australia.

Establishment of the Faculty of Veterinary Science at The University of Melbourne in 1909 and of the Department of Veterinary Science at the University of Sydney in 1910 (which became a Faculty in 1920) gave some impetus to the investigation of a range of infectious and parasitic diseases that long had troubled the Australian livestock industries (Caple 2011). Notable among these efforts was Sydney Dodd's work at The University of Melbourne on the aetiology of black disease (infectious necrotic hepatitis) in sheep (Edgar 1951). Despite purporting to cover all aspects of livestock research up to that time, Edgar's review reflects the early preoccupation with disease rather than production and its underpinning disciplines. It also is pertinent that most of the researchers he cited were employees of the Council for Scientific and Industrial Research (CSIR) or state agricultural departments, not university veterinary schools. Australia's capacity for veterinary research and education was further limited by closure of the Melbourne faculty to teaching in 1928, leaving Sydney as the only national option for veterinary training until 1936, when the School of Veterinary Science was established at the University of Queensland (Caple 2011).

Council for Scientific and Industrial Research

After a long gestation, commencing with formation of the Advisory Council of Science and Technology in 1916, the CSIR was established in 1926 despite some resistance from the universities and state research departments (Currie and Graham 1966). Among its first research divisions were Animal Nutrition and Animal Health, established in 1927 and 1930 respectively, reflecting contemporary perceptions of the major limits to livestock productivity (Fig. 1). These two areas of science were to be strongly supported by Sir David Rivett during his tenure as CEO of the CSIR from 1927 to 1946.

The first Chief of the Adelaide-based Division of Animal Nutrition was Brailsford Robertson, a pioneer of the emerging discipline of biochemistry, who died prematurely of pneumonia after only a couple of years in the post. He was followed by the eminent English pathologist and physiologist, Sir Charles Martin, who had a similarly short tenure before retiring to his homeland in 1933. Acting leadership of the Division before and after Martin's term fell to the youthful Hedley Marston, who had been a protégé of Robertson's at the University of Adelaide and who, over the next 30 years, would become one of the most significant and controversial figures in Australian science.

Marston's biographers paint the picture of a personality that was alternately domineering and charming, hard-nosed yet quixotic (Synge 1967; Underwood 1967). There is no doubt that Marston's personal drive, insight and wide range of interests did much to further the cause of animal nutrition in Australia and, indeed, the world. His documented achievements in sheep nutrition research include amino acid analysis of wool protein in relation to sulfur requirements; demonstration of microbial fermentation of cellulose to volatile fatty acids in the rumen; investigation of nutritional effects on energy balance and maintenance requirements; and discovery of requirements for various macro- and microminerals (Synge 1967). The latter body of work includes his major claim to fame, the discovery of the essential role of cobalt in preventing a suite of wasting diseases in sheep and cattle in various parts of the world, including coastal regions of his native South Australia. Marston's personal contribution to this discovery has been disputed by McDonald (1993), who provided evidence that, having initially ridiculed the notion of cobalt's essentiality, Marston appropriated responsibility for the successful research from his junior colleagues, Lines and Thomas. Further controversy was generated by Marston's refusal to acknowledge co-responsibility for the discovery by the almost simultaneous yet independent reporting of Filmer and Underwood on the role of cobalt deficiency in the aetiology of coastal disease in Western Australia (Synge 1967; McDonald 1993). Nevertheless, Marston's long-time bête noir, Eric Underwood, was gracious in acknowledgement of his rival's contributions to the work on cobalt deficiency, including his later work with RM Smith in defining its role in ruminal synthesis of vitamin B_{12} (Underwood 1967).

The first Chief of the Division of Animal Health, based in Melbourne, was the Scottish veterinary scientist, John Gilruth, who had been the foundation Professor of Veterinary Pathology at The University of Melbourne before his appointment as Administrator of the Northern Territory in 1912. Although politically disastrous, the latter experience apparently enthused him about the potential for northern beef production, particularly through the introduction of tropically adapted, tick-resistant Zebu cattle (Powell 1983). To this end, he was instrumental in arranging for the CSIR to acquire on loan the Queensland Government's Oonoonba Research Station near Townsville. In 1932, Gilruth sent a promising young veterinary pathologist, AW Turner, to be Officer-in-Charge (OIC) of the new laboratory. Turner was joined by the geneticist, RB Kelley, who, under Gilruth's direction, travelled to the USA in 1933 to select and import to Australia 19 Brahman cattle. This initiative was sponsored by a group of Queensland graziers, but was far from popular with the wider northern pastoral community who considered the humped

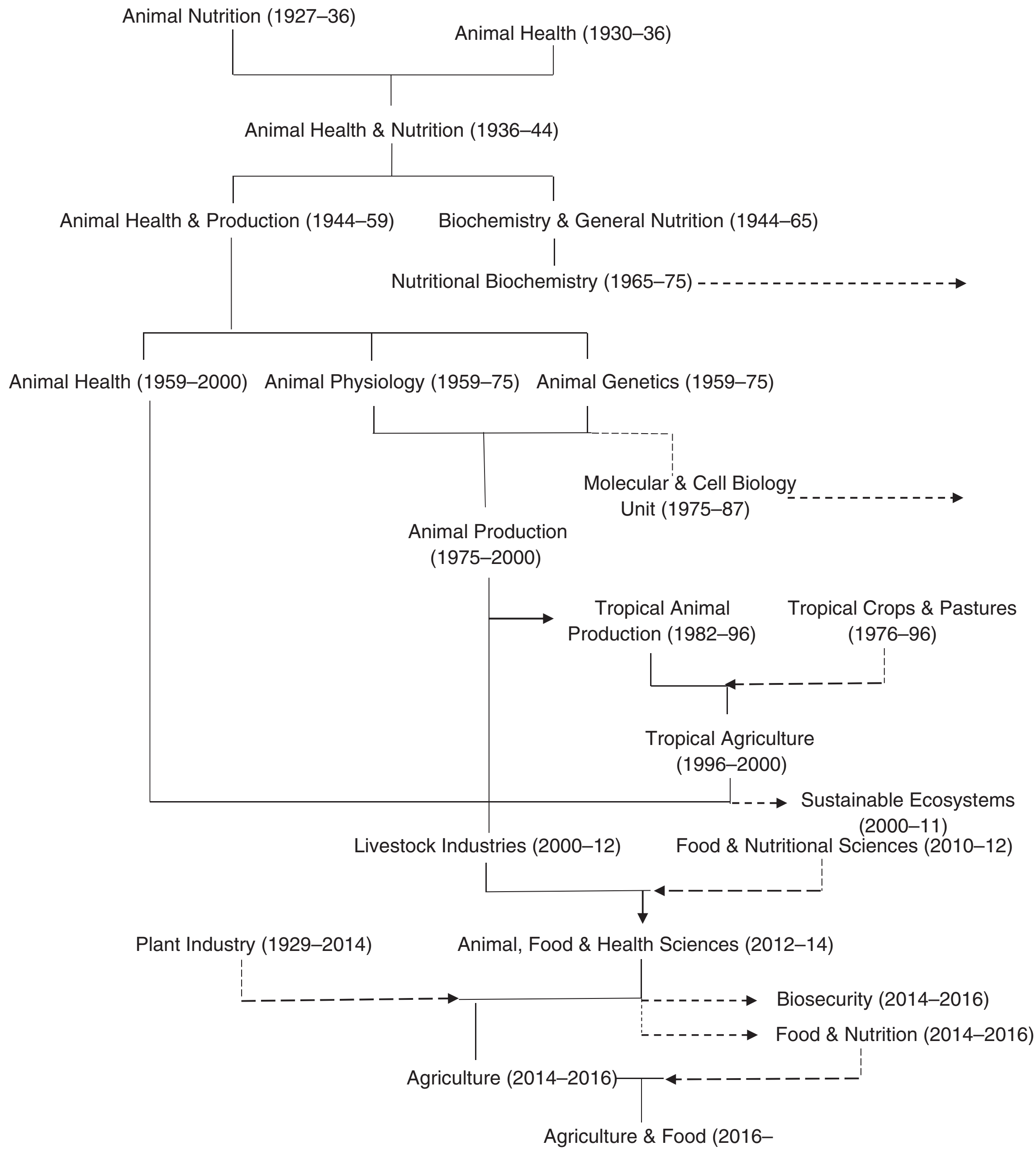

Fig. 1. Outline of the organisational history of the CSIRO Divisions serving the Australian livestock industries. Adapted from https://csiropedia.csiro.au/livestock-industries-2000-2012/ (accessed 17 February 2019).

imports to be inferior animals. This notion was gradually disproved by Kelley's long-term observations and reporting on the performance of the imported Brahmans and their progeny on five commercial properties across northern Queensland (Kelley 1943).

In the meantime, Turner embarked on studies of contagious bovine pleuropneumonia, which had become enzootic throughout northern Australia, with disastrous effects on beef productivity. Within 5 years, he and his team had produced a diagnostic test for and an effective vaccine against the disease, tools that were instrumental to the ultimate national eradication of the plague in 1973 (Newton 1992).

Another signal event in the early development of the Division of Animal Health was the opening of the FD McMaster Animal Health Laboratory on the Sydney University campus in 1931, enabled by an endowment of £20 000 by the influential grazier, (Sir) Frederick McMaster. The OIC of the new laboratory was a young veterinary parasitologist, Ian Clunies Ross, who quickly set about expanding the capabilities of his facility. One of his early appointees was the newly graduated W. I. B. Beveridge, who identified the causal organism of footrot in sheep (Beveridge 1941) and later became an international leader of the veterinary sciences while at the University of Cambridge (Anon 1959). Clunies Ross' subsequent major achievements as a research administrator and inspirational leader of the CSIRO are discussed in the next section.

Gilruth retired from the CSIR in 1935, to be replaced by his deputy Chief, Lionel Bull. Within a year of Bull's appointment as Chief of Animal Health, the two CSIR animal divisions were merged to form the Division of Animal Health and Nutrition (Fig. 1), with Bull as Chief. This amalgamation was deeply resented by Hedley Marston, who effectively was demoted to be OIC of the Animal Nutrition Laboratory in Adelaide. Bull, an accomplished bacteriologist, turned out to be a forceful and visionary leader. In addition to promoting the traditional animal health disciplines, he established sections of animal breeding and genetics and animal physiology and, to Marston's chagrin, recruited nutritionists to work at the McMaster Laboratory (French 1993). Notable among the latter was MC ('Frankie') Franklin, a New Zealand scientist appointed in 1939, whose subsequent contributions to ruminant nutrition are discussed in the next section.

Another key appointment to the McMaster Laboratory, also in 1939, was that of Australia's leading wool biologist, HB Carter, who would have a profound influence on sheep and wool production research in succeeding decades. Unlike most of his Sydney-based colleagues, Carter successfully established collaborations with his divisional colleagues in Adelaide, most notably in what became known as the 'Adelaide' experiment that examined the effects of genotype and plane of nutrition on wool growth in Merino sheep from birth to maturity. Commenced in 1940, this involved rail transport of a group of fine-wool lambs from a stud at Blandford, NSW, to Sydney, followed by a 10-day voyage to Adelaide, where they then were reared with locally obtained strong-wool lambs. Unfortunately, wartime exigencies and the administrative separation of Carter and the Adelaide group led by Hedley Marston were to prevent publication of this important study (Carter 2000).

Meanwhile, Marston persistently lobbied the CSIR's CEO, Sir David Rivett, with whom he was on good terms, to re-establish an independent Division of Nutrition. His goal was achieved in 1944 with creation of the Division of Biochemistry and General Nutrition, of which Marston was to be Chief until his death in 1965. Bull continued as Chief of the Division of Animal Health and Production until his retirement in 1954; 5 years later, his Division was split into the Divisions of Animal Health, Animal Genetics and Animal Physiology (Fig. 1).

The state departments

After World War I, leaders of state departments of agriculture, such as SS Cameron in Victoria, George Valder in NSW and GL Sutton in Western Australia, actively began to promote livestock research and advisory activities in addition to the ongoing departmental responsibility for regulation of animal diseases. This required the development of both scientific expertise and appropriate facilities. In several states, the former need was partly addressed by offering cadetships to enable undergraduate training in the veterinary and agricultural sciences; in return, the new graduates were bonded to work for the state department for at least several years. An early beneficiary of this practice was Eric Underwood (BScAgric 1928) in Western Australia, whose important work on cobalt deficiency in the 1930s has been discussed. Later examples included GL (Bill) McClymont (BVSc 1942) in NSW, David Wishart (BVSc 1941) in Victoria and George Moule (BVSc 1941) in Queensland, each of whom would go on to become an important Australian leader of research and education in the animal sciences. Notably, the latter three individuals, as well as contemporaries, such as FHW (Fred) Morley, were new veterinary graduates appointed to lead research on animal husbandry and production rather than disease. This presumably reflected the relative lack of training of agricultural science graduates in animal disciplines, such as nutrition, genetics and reproduction, as later highlighted by McClymont (1953), despite concerns in the late 1930s that veterinary students up to that time were not more exposed to the sciences underpinning livestock production (Talbot 1938).

In 1923, the capacity of the NSW Department for research on livestock diseases was greatly increased by the creation of Glenfield Veterinary Research Station in Sydney. Animal research facilities were also expanded and upgraded in other states, including those at the Werribee State Research Farm in Victoria and the Yeerongpilly Stock Research Station in Queensland. For much of the period between the wars, the research focus of these laboratories continued to be on livestock diseases. For example, during his tenure as Director at Glenfield (1923–36), Herbert Seddon and his colleagues investigated and published numerous papers on tuberculosis, blackleg, brucellosis, botulism, sheep flystrike and plant poisoning (Taylor 2002). During the same period, leading veterinary researchers in other state departments of agriculture included HW (Bill) Bennetts in Western Australia who, in 1931, developed a vaccine against enterotoxaemia (Fitzpatrick 2011), and John Legg in Queensland who elucidated the causal factors of bovine tick fever (Skerman *et al*. 1988).

Departmental research on livestock productivity during the 1930s was constrained by a lack of funds, the continuing priority given to disease problems and the political imperative to increase crop (especially wheat) production during the Great Depression. Nevertheless, during the 1930s, Underwood, Bennetts and their colleagues investigated a range of nutritional problems of sheep in the south-west and wheatbelt of Western Australia including their seminal research on cobalt and copper deficiencies (Moir 2002; Fitzpatrick 2011). In the eastern states, experimental farms that had been used mostly for stud breeding and demonstration of husbandry practices were increasingly used for production research, such as cross-breeding for lamb production at Trangie in western NSW, nutrition of beef cattle on tropical pastures at Tully in northern Queensland and pasture improvement for dairy production at various sites in Victoria. However, most of the benefits of investment in personnel and facilities to conduct research on livestock production in the late 1930s and early 1940s were not realised until after World War II, as discussed in the next section.

Before World War I, the newly formed departments of agriculture had taken on the role of educating and advising farmers, albeit in a somewhat *ad hoc* and unstructured fashion. This often overlapped with their responsibilities for inspection and regulation of plant and animal diseases, which in some cases was a deliberate policy of leaders, such as SS Cameron in Victoria (Cameron 1931). During World War I, the substantial loss of veterinary expertise from the state departments to the Australian Army Veterinary Corps (Caple 2014*a*) curtailed both the inspectorial and advisory services to the livestock industries. Subsequently, the departments gradually formalised their advisory and continuing educational activities such that by the late 1920s, terms such as 'extension' and 'field days' were coming into use for the first time in NSW (Mylrea 1990) and, presumably, the other states. From this time on, it became clear that, despite the personal inclination and industry visibility of university leaders, such as Sir Samuel Wadham, Australia would not adopt the American Land Grant model, and publicly funded agricultural extension would remain the almost exclusive responsibility of the state departments of agriculture.

Nevertheless, extension activities were often modelled on those first developed in American state universities. For example, the Better Farming Train that travelled throughout Victoria from 1924 to 1935, and a similar program that operated in NSW during 1927–1929, were clearly based on agricultural demonstration trains that served several American states during the first decade of the 20th century. The content of the lectures and demonstrations varied with the Victorian region to which the train travelled, with emphasis on dairy technology and production when in Gippsland, but on wheat growing when in the Wimmera and Mallee (Holmes and Mirmohamadi 2017). Other important, and longer-lived, vehicles for transferring technical and other information to farmers were the journals of agriculture, usually published monthly or quarterly by each of the state departments almost from their inception until they were superseded by more modern print and electronic media in the late 20th century.

Livestock extension priorities varied between state jurisdictions and industries during the 1930s. However, all states had dairy industries in which milk quality was perceived to be a greater problem than animal productivity. Thus, dairy hygiene and processing technology, together with herd testing and recording, were generally given priority. However, dairy productivity benefited greatly from state-sponsored research and extension on pasture improvement, often involving farmer participation, based on the use of phosphate fertilisers, and mixtures of new cultivars of grasses and clovers to increase carrying capacity and milk production per acre. These advances also boosted sheep meat and beef productivity, especially in the higher rainfall regions of southern Australia. In NSW and Western Australia, departmental advice to wool producers targeted general sheep management, ram selection and sheep classing (Mylrea 1990; Fitzpatrick 2011), whereas in Queensland, greater emphasis was placed on combatting flystrike and gut parasites (Skerman *et al*. 1988). Researchers in the Queensland Department of Agriculture were also early in addressing nutrition, breeding, and other issues of the emerging pig and poultry industries, through the respective leadership of Ernest Shelton and Percy Rumball (Skerman *et al*. 1988). Additional research into poultry diseases, nutrition and breeding was initiated at the NSW department's Glenfield and Seven Hills stations during the 1920s (Mylrea 1990).

Relations between research organisations

As discussed above, in the 1920s, increasing emphasis was placed on agricultural and veterinary research, spurred by the creation of the CSIR and growing scientific capability within the state departments of agriculture and, to a lesser extent, the universities. Inevitably, there was often tension over competition for relatively meagre public funding that was exacerbated by the Great Depression in the 1930s. However, there were also notable examples of cooperation and collaboration. These included the early recognition by the state departments of their need for well-trained agricultural and veterinary graduates that led department leaders, such as SS Cameron in Victoria and GL Sutton in Western Australia, and politicians, such as FW Bulcock in Queensland, to become key advocates for government support of the newly established university faculties of agriculture and veterinary science in their states. Other examples of cooperation were the willingness of The University of Melbourne to allow state use of research and diagnostic facilities at the Veterinary Research Institute in Parkville, the University of Sydney's hosting of the CSIR's McMaster Laboratory at its Camperdown campus and the Queensland department's loan of its Oonoonba Stock Experiment Station near Townsville to the CSIR to enable research on bovine pleuropneumonia and other aspects of northern cattle health and production during the 1930s. Also, in an era that preceded the growth, consolidation and role differentiation of organisations after World War II, there was considerable, lower-level cooperation through research collaborations, sharing of laboratory facilities, secondment of the CSIR and departmental staff to teach university courses, and involvement of the CSIR staff in advisory work.

Of course, there were exceptions to this generally positive scenario. For example, it has been stated that Hubert Mullett, Director of Agriculture in Victoria (1931–1955) 'kept CSIR and later, CSIRO out of most areas of agricultural research in Victoria' (Russell *et al*. 2014). Conversely, there is evidence that Hedley Marston from the CSIR did much to ensure that public funding of animal research in South Australia during the 1930s favoured his organisation. In this he was helped by the relative weakness of the South Australian department before World War II due to an act of parliament giving the University of Adelaide's Waite Institute a primary responsibility for state-sponsored agricultural research (Lohmeyer 1981).

Post-war expansion: the golden era 1945–1975

During the three decades after World War II, there was unprecedented growth in agricultural research, education and advisory services in Australia, particularly those relating to productivity of the pastoral industries. This expansion was driven by numerous factors, including political sympathy for agriculture, strong scientific leadership and economic opportunity. During the immediate post-war years, political decisions to increase funding for agricultural research, development and extension (RD&E) were especially influenced by two factors: first, the urgent need for rural reconstruction, including the training and support of inexperienced soldier settlers; and second, the demand for increased production of food and fibre to both generate export income and supply a rapidly growing domestic market (Russell *et al*. 2014). Some of this growth was seeded by key appointments and organisational structuring during the late 1930s and early 1940s, especially in the CSIR and state departments. Post-war development of research capacity and postgraduate training in the scientific disciplines underpinning livestock productivity within the universities was, however, a new phenomenon.

Political and scientific leadership

For much of the period covered in this section, agricultural RD&E in Australia benefited from a combination of political stability, and belief in the importance of higher education and science as drivers of prosperity. In particular, the Menzies government (1949–1966) greatly increased the direct funding of universities that previously had been considered a state responsibility, as well as introducing a generous Commonwealth scholarship scheme that stimulated rapid expansion of student numbers. At the same time, Sir John McEwan, the powerful leader of the Country Party and Deputy Prime Minister, ensured that agricultural education and research received a liberal share of these new resources. In addition, agricultural research in the CSIRO benefited greatly from the policies of its federal political sponsors. Most state governments were also sympathetic to agriculture, which was reflected in the growth of research and extension capacity, as well as resources for education in the agricultural colleges, within the state departments. For example, the Bolte government in Victoria (1955–1971) was led by a Premier who had been a western district sheep farmer and included a Minister for Agriculture, Sir Gilbert Chandler, who had been a professional horticulturist (Russell *et al*. 2014).

Agricultural research and education were also well served by a generation of visionary and highly effective scientific leaders. Notable among these was Sir Ian Clunies Ross, the far-sighted and politically astute Chairman of the CSIRO (1949–1959), who not only greatly furthered the cause of his own organisation, but was a major contributor to the Murray Report of 1957 that led to a substantial boost in federal funding of the public university system. As previously mentioned, Clunies Ross had been OIC of the CSIR McMaster Laboratory before the war. He was appointed Professor of Veterinary Science at the University of Sydney in 1939, but during and after World War II he assumed numerous additional roles as an influential advisor on national policies for agriculture, especially the wool industry, and broader aspects of scientific and technical manpower development. This experience led to his appointment to the executive committee of the CSIR in 1946 and to chairmanship of the reformed the CSIRO in 1949 (Schedvin 1993). Among the numerous achievements of Clunies Ross was the establishment of the CSIRO Sheep Biology Laboratory at Prospect in western Sydney that opened in early 1954 and would be named after him posthumously. The first permanent OIC of the new laboratory, appointed later in 1954, was Ian McDonald, whose academic credentials included a Diploma in Agriculture from Hawkesbury Agricultural College, a BVSc from Sydney University and a PhD in nutrition from Cambridge, where he studied under Sir Joseph Barcroft and Professor AC Chibnall (Ferguson 2003). McDonald would later become the inaugural Chief of the Division of Animal Physiology in 1959 (Brown 2010; Fig. 1).

The universities and state departments of agriculture were also blessed with strong leaders during the post-war decades, many of whom either were British in origin or, like McDonald, had received postgraduate training in British universities. Among these was Eric Underwood, who had emigrated to Western Australia from England as a small boy, received a first degree from the University of Western Australia and a PhD from Cambridge, and was appointed Dean of Agriculture at his *alma mater* in 1946. Other nutritionists who became influential academic leaders were GL (Bill) McClymont and RL (Bob) Reid, both of whom had trained under Sir Joseph Barcroft at Cambridge, and Derek Tribe, an English scientist who received his research training at the Rowett Institute in Scotland. McClymont and Reid respectively became the Foundation Deans of Rural Science at the University of New England (UNE; 1955) and of Agriculture at La Trobe University (1968), while Tribe was appointed Dean of Agriculture at The University of Melbourne in 1969. Notably, Underwood and McClymont had previously made important research contributions while employed by the Departments of Agriculture in Western Australia and NSW respectively before assuming university leadership, as had Reid with the CSIRO.

Within the state departments, several animal scientists became very successful Directors-General or Under-Secretaries during the post-war decades. For example, David Wishart, formerly Senior Veterinary Officer in the Victorian department, presided over significant administrative reorganisation and expansion of research facilities during his tenure as Director and Director-General from 1967 to 1979 (Caple 2014*b*; Russell *et al*. 2014). During this period, the department's SS Cameron Laboratory at Werribee gained an international reputation for its research on the reproductive physiology of livestock, consistent with the Director's personal interest and research achievements in this field (Russell *et al*. 2014). In the Queensland department, JM Harvey, who had earned a DSc for his research on fluorosis in sheep during the 1930s, and had been head of the biochemical branch of the Animal Research Institute, also provided strong leadership during his tenure as Director-General and Under-Secretary of Agriculture from 1965 to 1976 (Skerman *et al*. 1988).

Changes in funding mechanisms and opportunities

The early post-war period saw major changes in the mechanisms and levels of funding for agricultural research, development, extension and education, some resulting from far-sighted political and scientific leadership, as discussed above, and others driven by market forces particular to this period. Key elements considered in the following discussion are the evolution of the unique Australian model for government leveraging of industry funding for research, initially applied to the wool industry; specific changes in policy that greatly increased the opportunity for universities to be involved in agricultural research and postgraduate training, and for state departments to undertake extension; the positive impact of the wool boom of the early 1950s on RD&E funding; and the negative effects of falling wool prices and the UK's entry into the EEC in the early 1970s.

In 1936, the Australian Government established a compulsory producer levy for funding wool promotion and research. This scheme evolved during the early post-war period into a system whereby the government matched the levy funds devoted to research and development, and a statutory advisory committee – the Wool Research Trust Fund – administered distribution of the funds (Zhou 2013). Although this system was not applied to other agricultural industries until the 1980s (discussed in the next section), the model set a precedent that strongly influenced its later adoption by those industries. A major beneficiary of the Wool Research Trust Fund was the CSIRO Sheep Biology Laboratory at Prospect, which received over 80% of its total support via block funding from this source until the late 1960s. Depressed wool prices during the early 1970s led to this fraction being reduced to 62% by 1974, a trend that continued until block funding ceased in 1990 (Brown 2010).

Other federal government policy initiatives would have far-reaching effects on the capacity of universities to conduct research and train future scientists. These included adoption of the recommendations of the Mills Committee in the early 1950s to increase Commonwealth funding of the universities, and, most significantly, the advice of the Murray Committee in 1959 for the Commonwealth to contribute substantially to both recurrent and capital funding. This resulted in rapid expansion of facilities for teaching and research, including establishment of new universities with schools of agriculture (La Trobe 1964) and veterinary science (James Cook 1969, Murdoch 1975), and rates of growth in student enrolments that exceeded 10% per annum during the early 1960s (Abbott and Doucouliagos 2003).

Commonwealth policies initiated soon after World War II also stimulated major expansion of extension services offered by the state departments. These included the Commonwealth Dairy Industry Grant first offered in 1948–49 and the Commonwealth Extension Services Grant first offered in 1952–53. These two sources were amalgamated in 1966 and amounted to $4.4 million in 1968–69 (Australian Bureau of Statistics 1969). These grants supported overseas travel and training – particularly in USA Land Grant Universities – development of extension leadership, and extensive in-house training opportunities for extension officers in state departments. A notable example was the training program initiated and managed by George Moule of the Queensland Department of Agriculture after his return from a study tour of the USA in 1952 (Skerman *et al*. 1988). This program was designed primarily to meet the needs of staff in his own department, but attracted extension personnel from other states, including Peter Hyland from Victoria, who provided a glowing testimony of its value (Russell *et al*. 2014). For at least a decade from 1952, the Commonwealth also supported state extension services to the wool industry via the Sheep and Wool Extension Course organised and delivered by staff at the CSIRO's McMaster Laboratory in Sydney, an activity strongly encouraged by the CSIRO Chairman, Ian Clunies Ross (Russell *et al*. 2014). Sadly, this much-valued cooperative venture was to disappear from the CSIRO's portfolio, as the Organisation sought to differentiate its agricultural scientific responsibilities from those of the states.

Market forces also had a major influence on funding available for agricultural RD&E during the post-war decades. The most striking example was the spectacular, but transient, increase in wool prices driven by the release of British control of the Australian wool clip after World War II and USA demand for wool to clothe its soldiers during the Korean War in the early 1950s. As discussed above, this drove generous support of research and development by the wool industry until the early 1970s, when uncertain prices and a faltering general economy led both industry and government to question the return on their respective investments. Another market-related event that would have far-reaching impact on industry structures and capacity to fund RD&E was Britain's entry into the EEC in 1973. This had an especially profound negative effect on the dairy industry, but also affected the value of other livestock commodities previously exported to the UK, including lamb and beef.

Development and achievements of the major animal science disciplines

The meta-disciplines underpinning research to improve the productivity of healthy livestock include nutrition, reproductive biology and genetics, also known as the 'feeding and breeding' sciences. Australian contributions to the depth and breadth of knowledge in each of these areas grew enormously during the period in question, to a level belied by the size of the country's research community and expenditure devoted to improving livestock production. Examples of leadership and key achievements are briefly discussed below.

Already prominent nutritionists, such as Hedley Marston, Eric Underwood (both later elected Fellows of the Royal Society), MC Franklin and Ian McDonald, continued to make important personal contributions to their field, as well as influencing future leaders in livestock nutrition and metabolism. Examples include Marston's elaboration, with Richard Smith, of the role of cobalt in rumen microbial synthesis of vitamin B_{12} (Marston and Smith 1952), Underwood's internationally acclaimed books on mineral nutrition of livestock and humans (Underwood 1977, 1980), Franklin's highly applicable research on drought feeding of sheep and cattle (Franklin 1951), and McDonald's demonstration of the extensive ruminal degradation of dietary nitrogen sources and the nutritional importance of microbial protein synthesis within the rumen (McDonald 1954).

Underwood's close colleague at the University of Western Australia, Reg Moir, became internationally recognised for his research on multiple aspects of ruminant nutrition, most notably rumen microbiology, digestion and metabolism (Moir 1951, 1957). The breadth of Moir's interests, achievements, and influence on students and colleagues is illustrated by the published contents of a symposium held in his honour in 1984 (Baker *et al*. 1984). Franklin greatly influenced the direction of Bob Reid's research at the CSIRO Prospect on energy nutrient metabolism and metabolic disease in sheep (Reid 1968), while McDonald's protégés at the same laboratory included Jim Hogan, Bob Weston, Norman Graham and later, Graham Faichney, who would make seminal contributions to the understanding of digestive physiology and energy metabolism in ruminants, and applications to feeding practice (Weston and Hogan 1967; Graham and Searle 1972; Faichney 1975). The pastoral industries were also well served by several CSIRO scientists of British origin, including Dennis Minson, working on the nutritional value and intake of tropical forages (Minson 1972), and John Wheeler and Harry Stobbs, working on grazing behaviour and management of sheep and cattle in different climatic zones (Wheeler *et al*. 1963; Stobbs 1973).

Meanwhile, during the late 1950s and early 1960s, Bill McClymont was establishing a strong department of nutrition and biochemistry at UNE, mostly through recruitment of talented young scientists from the UK and elsewhere abroad. These included Frank Annison, Derek Lindsay and, later, Ron Leng from England, who pioneered isotope dilution techniques to quantify intermediary metabolism in sheep (Annison *et al*. 1967), and Rob Cumming and David Farrell from South Africa and Ireland respectively, who established UNE as the leading site of poultry nutrition research in Australia (Farrell *et al*. 1973). Prominent among Leng's numerous students and associates was John Nolan, who, during his long career at UNE, became an international leader in quantitation and modelling of ruminant nitrogen metabolism (e.g. Nolan and Dobos 2005). Another notable early appointee at UNE was Neil Yeates, a CSIRO scientist who had trained at Cambridge under Sir John Hammond during the 1940s. Yeates' diverse interests and accomplishments in meat science, photoperiodic control of reproduction, climatic adaptation and wool production are summarised in his textbook, *Modern Aspects of Animal Production* (Yeates 1965).

Animal nutrition was also well represented at The University of Melbourne during this period through the work of Norman Tulloh on the effects of nutrition on patterns of growth of livestock (Tulloh 1963), of Geoff Pearce on fibre digestion in sheep and pigs (Pearce 1967), and of Tony Dunkin on energy and protein nutrition of pigs (Dunkin *et al*. 1986). Each of these university scientists – as well as their contemporaries Bill Allden, Adrian Egan and Alan Snoswell at the University of Adelaide, and John Ternouth at the University of Queensland – would have a significant influence on livestock production, as well as on the next generation of Australian animal nutritionists.

Research on causes of infertility and other reproductive maladies was conducted before World War II, including Bill Bennetts' investigations of ovine clover disease in Western Australia (Bennetts *et al*. 1946). However, compared with expertise in animal health and nutrition, that in reproductive biology was underrepresented in most Australian livestock research organisations before the 1960s. Early post-war pioneers of the field were Rodger Watson of the CSIR/CSIRO (1936–1961) and, later, the Victorian Department of Agriculture (1961–1979); David Wishart, also of the Victorian Department; Clifford Emmens of the University of Sydney (1948–1978); and Bennetts' Western Australian protégé, Terry Robinson, who trained with Sir John Hammond at Cambridge, commenced his postdoctoral career at The University of Melbourne (1951–1955), and later became Professor of Animal Husbandry at the University of Sydney (1956–1984). Watson is best known for his work on various causes of reproductive wastage, including lamb mortality, in the southern Australian sheep flock (Watson 1957), as well as his leadership in promoting reproduction research and its application within the Victorian department. Emmens migrated from his native England to become the inaugural head of the Department of Veterinary Physiology at the University of Sydney, which, for much of his tenure, was almost totally devoted to research on reproductive physiology. During the period 1952–1954, he was seconded to be OIC of the newly created CSIRO Sheep Biology Laboratory at Prospect (Brown 2010). Wishart is regarded as the father of artificial breeding of dairy cattle in Australia because of his pioneering research at the State Research Farm, Werribee, which began in the early 1940s (Wishart 1956; Caple 2014*b*). Robinson addressed many issues of reproductive performance in ruminants, most notably regulation and manipulation of the oestrus cycle in sheep (Robinson and Lamond 1966).

Watson's successors at the CSIRO, later mostly located at the Prospect laboratory, included his young Parkville colleagues, George Alexander, who would become an international expert on causes of neonatal mortality (Bell 2019), and Max Radford, who combined research on the neurophysiological control of reproductive processes with more applied work on detection and manipulation of cycling in the field (Radford *et al*. 1960). During the 1960s and 1970s, the Prospect laboratory became internationally renowned for its research on female and male reproduction that exploited a powerful combination of the expertise of endocrinologists, such as Alan Wallace, John Bassett and Ron Cox, with the surgical and experimental prowess of physiologists, such as Geoffrey Waites, Brian Setchell, Phil Mattner and Geoff Thorburn (Setchell *et al*. 1969; Bassett *et al*. 1970; Cox *et al*. 1971).

Clifford Emmens combined high expertise in reproductive biology, including manipulation of semen and development of oestrogenic bioassays, with advanced skills in biometry. He was also regarded as an excellent administrator (Stone and Wales 2004). Among his most accomplished students was Bernie Bindon, who, as a CSIRO scientist, made major contributions to reproductive biology and technology, including elucidation of mechanisms underlying the high ovulation rates of the Booroola Merino ewe and vaccination against inhibin to enhance fertility in sheep (Entwistle *et al*. 2006). Bindon would later become the successful CEO of the first two Beef Cooperative Research Centres (see next section).

Terry Robinson was also to have a major influence on the development of his discipline both at Sydney University and elsewhere. One of his first PhD students was David Lindsay who, after postdoctoral experience in the USA and a short stint on the staff at his Sydney *alma mater*, in 1967 began a long and illustrious career at the University of Western Australia. Lindsay, in turn, trained many budding reproductive biologists including Graeme Martin, now Winthrop Professor of Animal Biology at the University of Western Australia, and Chris Oldham, recently retired after a long, successful career with the Department of Agriculture and Food, Western Australia (DAFWA). Lindsay is internationally known for his research on the reproductive behaviour of sheep (e.g. Lindsay 1979), as well as other aspects of reproductive biology and management. He was also a part-time Merino breeder who, in 2008, achieved local fame for producing the finest bale of wool ever sold in Western Australia.

The group of reproductive biologists led by Terry Robinson at Sydney University included Neil Moore and Steven Salamon, who pioneered the use of artificial breeding and embryo transfer in sheep in Australia (Moore 1970; Salamon and Maxwell 2000). The first human embryo created by *in vitro* fertilisation, achieved by Carl Wood and his team at Monash University in 1973, was clearly influenced by Moore's earlier success in sheep. Also, Moore trained Alan Trounson who would become famous for his contributions to the development and widespread application of *in vitro* fertilisation in humans (Trounson and Moore 1974; Trounson *et al*. 1981). As noted earlier, the Victorian department's SS Cameron Laboratory achieved international recognition for its research on reproductive physiology during the period in question. Leaders included Robin (Ras) Lawson, who refined techniques for egg and embryo transfer in sheep and cattle (Lawson *et al*. 1983), and Jim Goding, who, although employed by The University of Melbourne, worked full-time at the Cameron Laboratory and is best known for his contributions to the discovery that prostaglandin $F_{2\alpha}$ is the uterine luteolysin in sheep (Goding 1974).

Much of the Australian research on sheep reproduction up to the early 1980s is reviewed in a book published by the Australian Academy of Science and the Wool Corporation (Lindsay and Pearce 1984), with contributions from most of the scientists cited in this section, as well as many others.

Apart from the research of Emmens, Wishart and others on the refinement of artificial insemination technology in dairy cattle, work on bovine reproduction was slower to develop. However, following the widespread introduction of Brahman and *B. indicus* cross cattle to northern Australia in the early post-war decades, producers' concerns about the relatively poor reproductive performance of these cattle began to be addressed during the 1970s by scientists, such as Keith Entwistle at James Cook University in Townsville and Dick Holroyd of the Queensland Department of Primary Industries (Entwistle *et al*. 1980).

Compared with other disciplines underpinning livestock production, lactation biology has not been strongly represented in Australia. An exception has been the Camden-based dairy science group within the faculties of Agriculture and Veterinary Science at the University of Sydney. The group was led by Alexander (Alick) Lascelles during his term as Professor of Animal Husbandry (1964–73). Lascelles, who had trained at the Australian National University (ANU) under the eminent immunologist, Bede Morris, made important research contributions to the understanding of mammary lymphatic function and protection against mastitis, as well as the role of colostrum in providing passive immunity to young calves (Husband and Lascelles 1975; Lascelles 1979). After his appointment as Chief of CSIRO Animal Health in 1973, Lascelles was succeeded by Frank Annison, who, in 1974, returned from England after a very fruitful, long-term research association with the internationally pre-eminent mammary biologist, Jim Linzell (e.g. Bickerstaffe *et al*. 1974). Both Lascelles and Annison devoted much effort to development of the role and resourcing of the Dairy Research Foundation at Sydney University (Annison 2007), which enabled important contributions to lactation biology and production to be made by a long list of their students and colleagues, including Peter Hartmann, Graham McDowell, Jim Gooden, Ian Lean and Bill Fulkerson (McDowell *et al*. 1987; Bramley *et al*. 2008). Hartmann, whose early research was on the lactation physiology of pigs and ruminants, would go on to become an international expert on human lactation during his long career at The University of Western Australia (Pang and Hartmann 2007).

As discussed earlier, considerable progress was made in practical aspects of plant and animal breeding in Australia during the century before 1950. However, the development of the discipline of genetics, especially as it related to livestock species, was remarkably slow in the universities and CSIR (McCann and Batterham 1993). Fred Morley was among the earliest Australian animal scientists to receive postgraduate training in the relatively new discipline of quantitative genetics. As a newly graduated veterinarian, he was appointed in 1943 to lead research on sheep breeding at the NSW Department of Agriculture's Trangie Agricultural Research Station in western NSW. In 1946, Morley was awarded a CSIR studentship to undertake PhD research in genetics with Jay Lush at Iowa State University (Anon 1990). Lush is regarded as the leading livestock quantitative geneticist of his time and Morley was an apt pupil. Upon returning to Trangie, he continued with the first genetic analyses of Merino sheep and established selection lines for important production traits. These unique genetic resources continued to be used for many years by his successor, Bob Dun, and others after Morley left the NSW department to join the CSIRO Division of Plant Industry in 1954.

Ian Clunies Ross was well aware of Australia's deficiencies in the capacity for teaching and research in genetics and, typically, did as much as anyone during the late 1940s and early 1950s to address the problem. In particular, he sought and acted upon advice from Lush and other international leaders of the field to create strong research programs in plant and animal genetics within his organisation, respectively led by Otto Frankel and Jim Rendel, culminating in the creation of the CSIRO Division of Animal Genetics in 1959, with Rendel as the inaugural Chief. Rendel was an Englishman with an impeccable scientific pedigree, having trained at University College London under the great JBS Haldane, and worked on dairy cattle genetics with CH Waddington at the University of Edinburgh (Franklin *et al*. 2004). He is rightly considered to be one of the founding fathers of animal genetics in Australia, both as an accomplished theoretical geneticist and a practical animal breeder, as well as a leader who recruited talented researchers and gave them the independence to get on with the job. Rendel's students include Stuart Barker, who, like his mentor, combined fundamental studies on *Drosophila* with applications to livestock breeding (Barker 1967), and Bruce Sheldon, who became Australia's leading poultry geneticist (Sheldon 2000; Pym *et al*. 2004). Among Rendel's star recruits was Ian Franklin, an Adelaide graduate who had received his postgraduate and postdoctoral training in the USA, and would go on to make important contributions to theoretical aspects of population genetics and conservation biology (Franklin 1980), as well as to practical breeding of sheep and cattle.

Another of Clunies Ross' gifts to livestock genetics was his protégé, Helen Newton Turner, who became the internationally pre-eminent sheep geneticist of her time during the post-war decades. Not recognising opportunities for a scientific career in the late 1920s, the mathematically gifted Newton Turner trained as an architect before becoming secretary to Ian Clunies Ross, then OIC of the McMaster Laboratory of the CSIR Division of Animal Health (Allen 1995). Her boss quickly recognised her potential, and in 1938 sent her to England for a year's training in statistics with (Sir) Ronald Fisher and Frank Yates, two of the world's leading statisticians. On her return to Sydney, she was appointed Consulting Statistician to the Division of Animal Health and Nutrition. After the war, her interests turned to the application of new quantitative genetic techniques to sheep breeding, and in 1956 she was appointed Leader of the Animal Breeding Section in the Division of Animal Health and Production (Allen 1995; Newton Turner 1996). From then until her retirement from the CSIRO in 1973, Newton Turner and her colleagues laid the foundation for an objective, measurement-based approach to breeding sheep for wool production and other important traits (see Turner and Young 1969) that remains in use today.

The CSIRO Division of Animal Genetics was actively involved in the breeding of tropically adapted cattle at Rockhampton in central Queensland, a major achievement of which was the development and release to industry of the Belmont Red breed by Jim Rendel and HG (Greig) Turner (Turner 1975). The breed was named after the cattle station, 'Belmont', north of Rockhampton that had been purchased in 1952 by the Australian Meat Board for use as a CSIRO research station. As OIC of the station, Turner, with John Vercoe, John Frisch and others, also conducted valuable research on the functional bases of heat tolerance, tick resistance, and other aspects of tropical adaptation in pure- and crossbred *B. indicus* cattle during the 1960s and 1970s (Turner and Short 1972; Frisch and Vercoe 1977). Vercoe would later lead the group during a very successful period for the CSIRO at Rockhampton, including the transfer in 1981 of laboratory operations from 'Belmont' to a modern, purpose-built facility in the city, aptly named the JM Rendel Laboratory.

Other influential Australian livestock geneticists whose careers began in the decades in question include John James from the School of Wool Technology at the University of New South Wales (1962–1997), Frank Nicholas from the Department of Animal Husbandry at the University of Sydney (1974–2007), and Keith Hammond from the NSW Department of Agriculture and UNE (1973–1993). James is regarded by his peers as Australia's leading scientist of his time in quantitative genetics and the theory of genetic improvement (Kennedy 2010). Nicholas made important contributions to theoretical aspects of population, quantitative and molecular genetics, and their application to livestock breeding (Nicholas 1980; Bovenhuis *et al*. 1997), as well as being the sole author of two widely used books on veterinary genetics (Nicholas 1987; 2009). He also conducted important research on the potential contribution of advanced reproductive technologies to expedite the rate of genetic improvement in dairy cattle and other livestock species (Nicholas 1996). Hammond, a student of Stuart Barker, in 1976 became the inaugural Director of the Animal Genetics and Breeding Unit (AGBU), a joint venture between the NSW Department and UNE, based on the UNE campus. Under his leadership, AGBU scientists became internationally recognised for their application of sophisticated statistical tools, such as best linear unbiased prediction (BLUP) for practical genetic evaluation of livestock. The Unit continues to have a major impact on animal breeding practice in Australia and, increasingly, overseas (AGBU 2019).

Emerging fields of study

During the late 1960s and early 1970s, several fields of study now considered to be central to the performance and public acceptance of the livestock industries began to emerge. Some, such as animal behaviour, were adapted from existing disciplines that had been applied to non-agricultural species. Others, such as the modelling and analysis of complex grazing systems, required integration of major disciplines, such as animal nutrition, pasture agronomy and animal behaviour, together with application of increasingly powerful computer technology. Computerised modelling approaches also began to be applied to integrate and understand biological complexity within the animal, with the prediction of productive performance under different conditions as a practical goal. In addition, this period saw the emergence of molecular technologies that later would become applied to advance genetic improvement and non-genetic management of livestock.

Initially, the main driver for investigating the behaviour of livestock was the opportunity to improve productivity, especially in the intensively managed pig and poultry industries. However, by the early 1970s, public concerns about animal welfare provided an additional stimulus to behavioural research in Australia and other developed countries, as reviewed by Alexander (1982). Australian pioneers in the field included Rolf Beilharz at The University of Melbourne, who combined his expertise in genetics with interests in behaviour and welfare (Beilharz and Zeeb 1981), and George Alexander at the CSIRO Prospect, who, in the 1970s, extended his detailed investigations on physiological limits to lamb survival to studies of perinatal ewe–lamb behaviour (Walser and Alexander 1980).

During the 1950s and 1960s, Bill McClymont at UNE was instilling in undergraduates the importance of understanding soil–plant–animal interactions in grazing systems as part of his vision of the agricultural ecosystem. Although he was not directly involved in leadership of research in this area, his vision inspired numerous others to undertake research on grazing systems, initially focused on productivity, but later including environmental stewardship as a main driver. Much of the early work in this field was applied to the modelling of sheep production systems by CSIRO scientists, such as Fred Morley in Canberra, Graham Arnold in Perth and the group led by John Wheeler at Armidale. Later, the CSIRO work on temperate pastoral and mixed farming systems was led by Hugh Dove and Andrew Moore from the Division of Plant Industry at Canberra. Bill Allden and his colleagues at the Waite Institute in Adelaide also made significant contributions to the field. Other CSIRO scientists, led by Harry Stobbs, used similar approaches to study tropical and subtropical beef cattle grazing systems in Queensland.

Development and application of the modelling of individual animal systems will be discussed later in this article. However, it should be noted that Australian work in this field had commenced by the early 1970s, with an initial focus on computer simulation of growth and production of sheep by John Black, Norman Graham and Graham Faichney at the CSIRO Prospect (Graham *et al*. 1976). Importantly, the success of this initiative was underpinned by the experimental data on quantitative digestion and metabolism obtained by these scientists. A pivotal event around this time was the sabbatical visit of an eminent modeller, Lee Baldwin, from the University of California at Davis, to work with John Black at Prospect in 1975 (Bell 2019). The synergy developed during this collaboration was to have a major impact on the future growth of the field within Australia and internationally.

Professional societies and scientific conferences

Growth of the animal science disciplines in Australia during the latter half of the 20th century was fostered by the formation of professional societies, which organised regular conferences to enable reporting of new findings, and promote debate and communication within the relevant RD&E communities. Most of these fora have featured excellent science that has attracted considerable international interest, as well as attendance and participation by leading producers and agribusiness professionals. The societies include the Australian Society of Animal Production, founded in 1951, which covers the biology, production and management of all livestock species; the Australian Society of Reproductive Biology, founded in 1968, which deals with reproduction in species of both agricultural and biomedical interest, including humans; the Association for the Advancement of Animal Breeding and Genetics (formerly the Australian Association of Animal Breeding and Genetics), founded in 1987, which covers all species of livestock; the Australasian Pig Science Association, founded in 1989; and the Australian Branch of the World Poultry Science Association, which, in conjunction with the Poultry Research Foundation at the University of Sydney, organises the Australian Poultry Science Symposium. Also, the Nutrition Society of Australia, founded in 1974, has offered a forum for animal nutritionists to interact with colleagues devoted to human nutrition; unfortunately, this involvement has waned considerably during the past couple of decades. It is interesting to note that, at the time of writing, the Australian Society of Animal Production is in the process of changing its name to the Australian Association of Animal Sciences to better reflect its membership of predominantly professional scientists, and the trend for producers to use other sources of applicable scientific information that are more focused on specific industry sectors and regions.

Other influential fora include the Recent Advances in Animal Nutrition (RAAN) (Australia) meetings and the Australasian Dairy Science Symposia (ADSS) that are organised by national or international committees rather than professional societies. The RAAN meetings, initiated in 1969, are held biennially at UNE, Armidale, while the ADSS, initiated in 2004, alternates biennially between different sites in Australia and New Zealand. The primary focus of these and the above-mentioned societal meetings is the biology, production and welfare of healthy livestock, whereas research on livestock diseases is the province of various veterinary science meetings, the most prominent of which is the Annual Conference of the Australian Veterinary Association (AVA), founded in 1921.

Role of Australian journals in fostering the animal sciences

In addition to the above fora to enable regular communication of research in the animal sciences, during the period in question, several Australian journals were established to publish peer-reviewed research on livestock biology and husbandry. Most of these were, and, under different names continue to be, published by the CSIRO. They include the *Australian Journal of Scientific Research*, Series B – Biological Sciences, the first issue of which was published in 1948 and included Hedley Marston's seminal paper on basal heat production in sheep (Marston 1948). In 1954, this outlet was renamed the *Australian Journal of Biological Sciences*, which continued to include papers on more fundamental aspects of livestock biology until its cessation in 1988. Since 1989, its previous content on reproductive and developmental biology in vertebrate species, including livestock, has been continued in *Reproduction, Fertility and Development*. In 1950, the CSIRO commenced publication of the *Australian Journal of Agricultural Research*, which, for several decades, included many papers on applied aspects of animal science before becoming mostly devoted to the plant and soil sciences. In the meantime, the *Australian Journal of Experimental Agriculture and Animal Husbandry* was initiated in 1969, changing in 1985 to *Australian Journal of Experimental Agriculture* and to its present title of *Animal Production Science* in 2009 (Bryden 2014). Although perhaps not prominent in terms of modern international indices, these CSIRO journals have consistently provided a platform for rigorously reviewed publication of Australian and, increasingly, international research on livestock biology, management and related topics.

In the realm of animal health, since 1925, Australia's flagship journal has been the *Australian Veterinary Journal*, currently published by Wiley. This internationally regarded journal publishes on clinical and more fundamental research into animal health, as well as on case studies and matters of professional interest to Australian veterinary practitioners.

Growth of extension services

The period immediately after World War II was one of unprecedented growth in staffing, physical resources and scope of activities of the state departments, including applied research and extension, as documented by Mullen *et al*. (2000). Some drivers, including political sympathy for agriculture, the need for post-war reconstruction and effective scientific leadership, have been discussed. Other factors included increased producer demand, presumably influenced by greater education and appreciation of the opportunities offered by scientific and technological innovation. Thus, the intensity of research and extension funding, defined as real expenditure divided by the value of production, peaked during the mid-to-late 1970s in each of the four states for which data are available, *viz* NSW, Victoria, Western Australia and South Australia (Mullen *et al*. 2000). Contrary to anecdotal perception, this analysis found no significant shift in the allocation of funds between research and extension in the state departments. Without evidence to the contrary, it is assumed that the data for total expenditure are broadly representative of patterns for the livestock industries.

Decades of uncertainty, organisational change and industry impact: 1975–2000

The last quarter of the 20th century was marked by considerable market volatility in the livestock industries, a steady decline in the contribution of these and other agricultural sectors to national income, and increased public questioning of industry practices, especially those relating to animal welfare and environmental stewardship. These factors led to reduced rates of growth in RD&E expenditure, and a quest for new models for the funding and conduct of research, as well as a shift in research priorities and perceptions of the need for publicly funded extension. The period also saw the dramatic rise in the development of new technologies, especially those underpinned by molecular biology and greatly increased computing power, as well as some industry disaffection caused by unrealistic promises from the research community about early benefits of these technologies.

Impact of market forces and changing public attitudes

During the mid-1970s, the beef and dairy industries suffered major price collapses, albeit for different reasons. Wool prices, in steady decline since the early 1950s, spiked transiently around 1973 and the late 1980s before resuming their previous negative trajectory; while for lamb, domestic consumption was in decline and export markets were weak. The rapidly restructuring pork and poultry industries also were affected by price volatility during this period, especially driven by fluctuating grain prices. These market conditions negatively affected the ability and willingness of producers to pay for research and development, particularly in the pastoral industries. During this period, the decline in the contribution of the livestock industries to national income, coupled with a softening of the broader economy, also led to reduced political enthusiasm for public funding of RD&E in support of these industries.

This deteriorating situation continued until the mid-to-late 1980s, when the Commonwealth Government established two institutions that would do much to stabilise and promote both the funding and conduct of agricultural research. These were the agricultural Research and Development Corporations (RDCs) and the Cooperative Research Centres (CRC) Program respectively.

Origins and evolution of the agricultural Research and Development Corporations

The principle of using industry levy funds, matched by federal government funds, to support agricultural RD&E was formalised and extended to most industry sectors in 1985 by the *Rural Industries Research Act*, which established the research councils that were precursors of the current RDCs. These councils allocated industry levy funds on behalf of commodity groups, and were accountable to the Commonwealth Government for the expenditure of matching funds (Zhou 2013). Industry and political concerns about coordination, uniformity and transparency of council functions led to reformation of the system in 1989 via the *Primary Industries and Energy Research and Development Act* to establish the basis of the current RDCs.

The RDC system was largely the brainchild of its chief political sponsor, John Kerin, an agricultural economist who was Minister for Primary Industries and Energy in the Hawke government from 1983 to 1991 (Kerin 2017). It has since evolved into a group of 15 organisations, of which nine are industry-owned corporations that fund both RD&E and marketing, and six are statutory authorities that, with exceptions, fund only RD&E. The livestock sectors are served by the seven industry-owned corporations listed in Table 3, with funding for some specific livestock programs, such as chicken meat, provided by the broad-based Rural Industries RDC. There are

Table 3. Research and development corporations (RDC) serving the Australian livestock industries
IOC, industry-owned corporation

Industry sector	RDC name	Year established: Statutory body	IOC
Chicken meat	Rural Industries[A]	1990	NA[B]
Dairy	Dairy Australia	1990[C]	2003
Eggs	Australian Eggs Limited	NA[D]	2002
Livestock export	Livecorp	1998	2005
Meat processing	Australian Meat Processor Corporation	NA[E]	1998
Pork	Australian Pork Limited	1990[F]	2000
Red meat	Meat & Livestock Australia	1991[G]	1998
Wool	Australian Wool Innovation	1972[H]	2001

[A]Now operating as AgriFutures Australia.
[B]Not applicable.
[C]Operated as Dairy Research & Development Corporation 1990–2003.
[D]Not applicable, funds were managed by the Rural Industries Research & Development Corporation 1990–2001.
[E]Not applicable, did not exist as a statutory body before formation as an IOC.
[F]Operated as Pig Research & Development Corporation 1990–2000.
[G]Operated as Meat Research Corporation 1991–1998.
[H]Operated as Australian Wool Corporation 1972 to 1991, then underwent several restructures before the establishment of Australian Wool Innovation as an IOC in 2001.

different views within and between industries on matters such as RD&E priorities, the balance of spending between research and marketing, and the lack of collaboration among the RDCs. However, it is the author's opinion that, by and large, the RDC system has served Australia well and has enabled a consistent level of funding that, in relative terms, is significantly greater than that available in other developed nations (Zhou 2013). This view appears to have been shared by successive federal governments, judging by their unwillingness to accept recommendations for significant change to the RDC system by the Productivity Commission (Australian Government 2012*a*) and other critics. A recent report, commissioned by the Federal Minister for Agriculture, recommended shifting the balance of public investment towards transformational and cross-sectoral outcomes, as well as seeking to attract greater private sector investment in agricultural innovation, but did not overtly criticise the RDC funding model (Ernst & Young 2019).

Collaborative Research Centres

Australia has been innovative not only in the way it provides funding to support agricultural RD&E, but also in the way it has fostered collaborative use of these funds, particularly via the CRC program. This program was established by the Hawke government in 1990 to stimulate industry-led collaboration among researchers, industry and the broader community to achieve research outcomes that will be readily adopted and, where relevant, commercialised. It is administered by the Commonwealth Department of Industry and Science, and during its almost 30-year history, has included CRCs focused on all of the major livestock industry sectors (Table 4). Most of these partnerships have included research contributions from multiple universities and state agencies, as well as the CSIRO, with co-funding and other support from relevant RDCs and additional industry sources. For example, the first Beef CRC received considerable financial support, including donations of cattle, from northern pastoral companies and individual graziers, while other producers and meat processors allowed CRC scientists to make measurements at their properties and processing facilities. Notable features of the livestock CRCs have been their strong leadership by senior scientists who are respected by research peers and industry (Table 4), and the prominent role in governance and oversight by leaders of the relevant livestock sectors.

The Commonwealth's financial contribution to the CRCs has, in addition to promoting collaboration among multiple research institutions and industry bodies, enabled significant leverage of funds provided by the partners, including the RDCs. For the five livestock industry sectors listed in Table 4, total funding since inception of the first Beef CRC in 1993 has amounted to almost \$285 million. Notwithstanding criticism about excessive bureaucracy and disputes among partners over intellectual property and other financial issues, the livestock CRCs have had an impressive list of achievements. Examples of industry impacts and benefits will be discussed later in this and the following section.

Research successes and industry impacts

Despite fluctuations in the economic fortunes of the Australian livestock industries and related uncertainty of research funding, the final decades of the 20th century saw some outstanding research successes and important benefits to industry. These were due in part to the scientific capacity and leadership built in the universities, state departments and CSIRO during the post-war decades, as discussed in the previous section. Many achievements were also facilitated by the creation of the RDCs and the CRC program, described above. Notable examples for each of the major livestock industry sectors are discussed below.

The 1970s were a bleak period for Australia's beef industry and its supporting research community, largely due to the collapse of its USA export market in 1974 caused by oversupply in both countries, and, to a lesser degree, the loss of its traditional British market with the UK's entry into the EEC in 1973. By the latter half of the next decade, fortunes were looking brighter, because the industry had gained access to high-

Table 4. Cooperative research centres (CRC) devoted to the Australian livestock industries

Industry sector	CRC name	Years of operation	Director/CEO	Program funding ($m)
Beef	Cattle and Beef Industry (Meat Quality)	1993–1999	Bernie Bindon	17.33
	Cattle and Beef Quality	1999–2006	Bernie Bindon	15.00
	Beef Genetic Technologies	2005–2012	Heather Burrow	30.00
Dairy	Innovative Dairy Products	2001–2009	Paul Donnelly	17.63
	Dairy Futures	2010–2016	David Nation	27.72
Pork	Internationally Competitive Pork Industry	2005–2012	Roger Campbell	23.81
	High Integrity Australian Pork	2011–2019	Roger Campbell	19.86
Poultry	Australian Poultry Industries	2003–2010	Mingan Choct	21.50
	Poultry	2010–2017	Mingan Choct	27.70
Sheep and wool	Premium Quality Wool	1993–1997	Laurie Piper	15.45
		1997–2000	Lionel Ward	
	Australian Sheep Industry	2001–2008	James Rowe	17.80
	Sheep Industry Innovation	2007–2014	James Rowe	35.50
	Sheep Industry Innovation	2014–2019	James Rowe	15.50
Cross-sector[A]	Emerging Infectious Disease	2003–2010	Stephen Prowse	17.50
	Developing Northern Australia	2017–2027	Jed Matz	10.00

[A]Includes industries or constituencies other than agriculture.

quality Japanese and other Asian markets. However, by the early 1990s, industry leaders, such as Rod Polkinghorne, President of the recently formed Australian Lot Feeders Association (ALFA), were becoming concerned by complaints from both Asian and domestic consumers about variation in Australian beef quality, especially tenderness.

The initial, industry-led response was to push for an ALFA-backed quality beef brand based on a yet-to-be-defined grading system. At around the same time, in 1992, the Meat Research Corporation (MRC), the research arm of the Australian Meat and Livestock Council, commissioned a large investigation into the causes of the decline in domestic beef consumption based on consumer assessment of beef quality. Findings of this study confirmed the industry's concerns about growing consumer resistance to Australian beef. Soon after, the first Beef CRC was formed, with improved eating quality as a central objective, providing a well-funded platform for a sustained scientific response to industry concerns. Early research leaders were John Thompson from UNE, who had trained at the University of Sydney with the eminent veterinary anatomist and meat scientist, Rex Butterfield, and Drewe Ferguson, a young meat scientist from the CSIRO. Soon afterwards, the research group expanded to form a multidisciplinary team that included Robyn Warner, a USA-trained meat scientist from the Victorian Department of Agriculture, David Pethick, a muscle physiologist from Murdoch University, and Ray Watson, a statistician from The University of Melbourne, as well as numerous other scientists and industry stakeholders. The chief outcome of their efforts was the Meat Standards Australia (MSA) beef quality assurance program, a predictive model based on extensive non-expert consumer assessment of eating quality with quantitative attributions to numerous pre- and postslaughter factors (Polkinghorne *et al*. 2008). The MSA program was commercialised in 1998 after several years of intensive research by the Beef CRC. In the 20 years since then, industry adoption has grown steadily, such that in 2017 it was applied to >40% of all adult cattle slaughtered in Australia (Polkinghorne 2018). An important contribution to this success has been the sustained research funding and promotion of the MSA system to industry and consumers by Meat and Livestock Australia (MLA).

In the 1970s, beef cattle in tropical Australia often did not reach market weight until 4–6 years of age because of marked seasonal fluctuations in pasture availability and quality (Poppi and McLennan 1995). This was not only inherently inefficient, but limited the product to low-value manufacturing beef. During the 1980s and 1990s, this problem was addressed by several groups of mostly Queensland-based scientists, including Stuart McLennan and Rob Dixon from the Queensland Department of Primary Industries; Bill Winter, Bob Hunter, Chris McSweeney, David Coates and others from the CSIRO laboratories at Brisbane, Rockhampton and Townsville; and Dennis Poppi and colleagues from the University of Queensland.

The research of these scientists was mostly directed at nutritional strategies to enable Brahman steers to reach carcass weights exceeding 300 kg by 2–3 years of age, allowing access to more lucrative markets. Much of this work focused on approaches to minimise dry season weight loss, including the now widespread practice of urea/molasses supplementation (Winks *et al*. 1979), use of alternative grazed and browsed forages, such as leucaena (*Leucaena leucocephala*; Winter *et al*. 1991), and implantation with hormonal growth promotants to reduce maintenance energy requirements during the dry season (Hunter and Vercoe 1987). However, even when dry season weight loss was minimised to less than 10% of total liveweight at the beginning of the dry season, it became apparent that a major limit to annual growth rates was lower than expected weight gain during the wet season (Poppi and McLennan 1995). These authors and Leng (1990) attributed much of this shortfall to asynchrony in the ruminal supplies of energy and nitrogen to optimise the postruminal supply of microbial and escape protein. Specifically, they concluded that the relatively low content of readily fermentable, non-structural carbohydrate in C4 tropical forages was insufficient to enable optimal use of rumen-degradable nitrogen sources for microbial protein synthesis. This interpretation was partly supported by later demonstration of growth responses to supplementation with energy (including that supplied by rumen undegradable protein sources) during the wet season (Mullik *et al*. 2011). However, the cost of supplements and feasible wet-season feeding systems remain a barrier to widespread industry adoption of these practices.

Until the 1970s, the Australian dairy industry was almost exclusively forage-based, and herd performance was assessed in terms of butterfat production per hectare of grazed pasture. This was reflected by a research focus on pasture agronomy, grazing behaviour and management, and forage conservation (e.g. Cowan 1975; Valentine and Radcliffe 1975). During the next several decades, there was a steady increase in the use of mostly cereal grain supplements (Garcia and Fulkerson 2005; Fig. 2). This was partly in response to concerns of producers and scientists that nutritional constraints affected the ability of exclusively pasture-fed cows to express their genetic potential. Other factors included processor payment systems

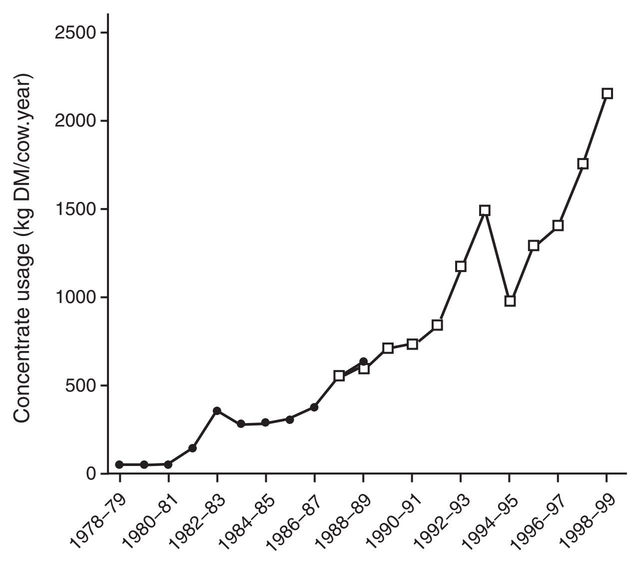

Fig. 2. Changes in the amount of concentrates fed to dairy cows in Australia between 1978–79 and 1998–99. Reproduced from Garcia and Fulkerson (2005), with permission from CSIRO Publishing.

designed to minimise seasonal variation in the milk supply and relatively low grain prices (Jacobs 2014). An early and influential scientific champion of supplementary feeding was Frank Annison during his tenure as Chair of Animal Science and Director of both the Dairy and Poultry Research Foundations at the University of Sydney between 1974 and 1994 (Annison and McDowell 1980; Bell 2019).

Although the feeding of concentrate supplements undoubtedly increased milk yield in grazing dairy cows, producers reported considerable variation in responses, which often were less than those predicted by estimated nutritional value of the combined forage and grain feedstuffs. This led to a sustained period of applied nutritional research, mostly supported by the Dairy Research and Development Corporation (now Dairy Australia), into factors contributing to dietary substitution and associative effects between feeds, such as the level of supplementation, forage quality and stage of lactation (Doyle *et al.* 2005). Much of this work was conducted at Victorian departmental research stations under the leadership of Peter Doyle and Chris Stockdale at Kyabram, and Graeme Rogers and Chris Grainger at Ellinbank. Similar studies under subtropical and tropical conditions respectively were led by Bill Fulkerson at the NSW department's Wollongbar station and Tom Cowan of the Queensland Department of Primary Industry and later, the Australian Tropical Dairy Institute at The University of Queensland. A key outcome of this research was the development of partial mixed ration feeding systems that, under appropriate conditions and management skills, have been shown to increase the profitability of Australian dairy farms (Wales and Kolver 2017).

Prior to the 1990s, the Australian prime lamb industry was mostly a by-product of the wool industry, based on the use of first-cross Merino (usually × Border Leicester) ewes mated to meat breed sires; first-cross wether lambs and cull ewe lambs were also used for meat. During the 1980s, the industry was suffering from declining consumption by the dominant domestic market, as well as depressed and uncertain export markets. For example, domestic consumption of lamb fell from 28 to 14 kg per person per year during the decade from 1971, apparently due to the product being considered too fatty and variable in quality (Centre for International Economics 2008).

Concerns about the future viability of the industry, particularly among terminal sire breeders, eventually led to an unprecedented national program of RD&E, together with product development and marketing, in the late 1980s and early 1990s that was coordinated by the MRC (now MLA) (Fogarty 2009). Early market research identified the commercial opportunities and production possibilities for heavier and leaner carcasses in both domestic and export markets. The R&D challenge was to provide producers with the tools to achieve this objective. Research up to the mid-1980s had focused on nutritional approaches, with only marginal success and industry penetration. Subsequently, the RD&E program was broadened to include genetic improvement. This required the development of sophisticated quantitative genetic approaches based on the use of BLUP to estimate breeding values derived from reliable, objective measurements of growth and carcass phenotypes.

The product for genetic evaluation and selection was LAMBPLAN, the development of which began in 1988 under the coordination of Rob Banks from the MRC. The project initially was co-funded by the MRC and the NSW Department of Agriculture, and in 1997 became an operating division and R&D program of MLA to enable commercialisation and industry ownership. Genetics research leadership was provided by Banks and Neal Fogarty from NSW Agriculture, and later, Daniel Brown from AGBU. The NSW Department also led the national program of centralised progeny testing of terminal sires that provided the phenotypic data needed for the derivation of estimated breeding values, particularly for growth rate and subcutaneous fat depth. This led to the demonstration that the amount of genetic variation in these traits between individual terminal sires was greater than that between terminal sire breeds (Fogarty 2009). This R&D program was later extended to evaluation of maternal breed sires, including Border Leicester, Corriedale, Coopworth and others.

LAMBPLAN was enthusiastically taken up by industry, especially the terminal sire sector, with the number of breeder registrations growing to >700 by 1996, and the number of animals registered in the database amounting to ~150 000 in 2004 (Barnett 2006; Fig. 3). Poll Dorset and White Suffolk breeders accounted for ~50% of breeder registrations. Rapid genetic progress in carcass size and leanness was embraced by

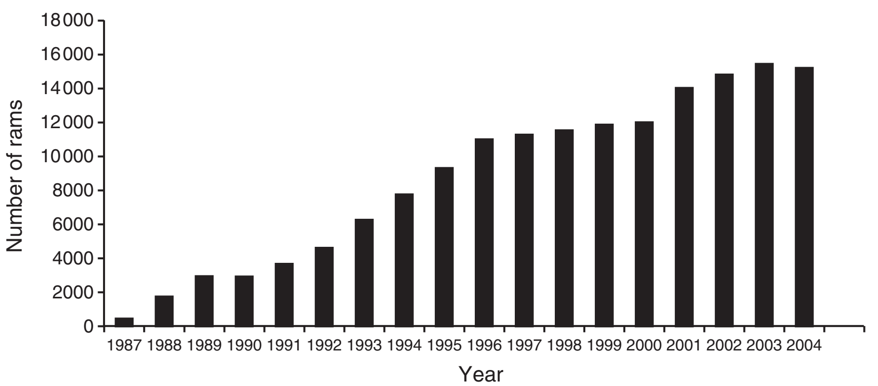

Fig. 3. Total number of rams produced by LAMBPLAN registered breeders with estimated breeding values between 1987 and 2004. Reproduced from Barnett (2006), with permission from Meat & Livestock Australia.

both domestic and export markets, most notably in the USA, leading to increases in the amount and nominal farm gate value of lamb production of ~1.5 and 3.8 times respectively between 1991 and 2006 (Centre for International Economics 2008). Accordingly, these achievements of the sheep meat industry and its scientific supporters can be regarded as one of the great successes of Australian agriculture during the late 20th century.

Unfortunately, the story of research on wool production during this period is not so rosy, due to mostly depressed markets that culminated in the abandonment of the reserve price scheme in 1991 and political infighting among industry leaders over how best to spend the declining pool of levy funds. As a result, research organisations with previously strong programs in wool production, most notably including the CSIRO, had greatly reduced their engagement with the industry by the early 2000s. Nevertheless, there were some outstanding research achievements, which, if the industry had been more receptive and patient, might have had significant positive impacts in the long term.

Among these was the 20-year development of biological defleecing technology by scientists at CSIRO Prospect that culminated in the commercial release of Bioclip™ in 1998. This procedure was based on the discovery that a single exogenous dose of epidermal growth factor causes a temporary break in wool fibres at the follicular level (Moore *et al*. 1982), allowing the fleece to be harvested manually at least a week later. Extensive studies of the mechanisms of action, practical efficacy, and contraindications of natural and recombinantly derived forms of epidermal growth factor were accompanied by the development of a retaining net to prevent premature loss of the fleece and avoid hypothermia or sunburn in the treated animals. Demonstrated advantages of the novel technology over traditional mechanical shearing included elimination of second cuts and skin lesions, reduced variation in wool fibre length, increased carding yield and reduced need for chemical control of parasites. However, the cost-effectiveness of the technology was marred by problems with early versions of the retaining net, the need to handle animals twice, unsuitability for use on pregnant (epidermal growth factor is an abortifacient) or larger (>50 kg) animals and the price of the injectable product. Consequently, the rate of industry adoption was modest, and the commercial product was withdrawn from the market in 2013. Nevertheless, the concept of biological harvesting of wool still has industry supporters and, with further development of existing technology or innovation of new approaches (e.g. Hynd *et al*. 2015), could yet play an important part in the Australian wool industry.

Other research on wool production, mostly conducted by partners in the CRC for Premium Quality Wool during the 1990s (Table 4), included further development of quantitative genetic techniques to select for wool weight and fibre diameter (Swan *et al*. 2008), and the use of genetic engineering approaches to create novel wool fibre characteristics in sheep (Bawden *et al*. 1998). There was scientific progress on both fronts. However, influential industry leaders considered that neither conventional nor molecular genetic approaches would do much to improve industry fortunes, at least in the short- to medium-term, and Australian Wool Innovation was directed to increase its investment in marketing at the expense of RD&E on wool production. Nevertheless, research on genetic improvement of wool production, including genomic selection, continued to be supported by subsequent Sheep CRCs, culminating in the development of MERINOSELECT by AGBU scientists in 2005 (see next section).

The rapid transformation of the Australian pork industry into a consolidated, independent agricultural sector during and after the 1960s was assisted by a series of impressive research achievements, particularly in feeding, nutrition and growth biology. Prominent among these was the work of two young nutritionists, Roger Campbell and Ted Batterham, both trained at The University of Melbourne by Tony Dunkin in the early 1970s. Campbell essentially rewrote the book on energy and protein requirements of baby, growing and finishing pigs, beginning during his doctoral studies and continuing at the Victorian Department's SS Cameron Laboratory in Werribee throughout the 1980s, in collaboration with his departmental colleagues, Mike Taverner and Ray King (Campbell 1988). During the same period, Batterham was conducting groundbreaking research on the availability and utilisation of amino acids for growing pigs at the NSW Department's Wollongbar Research Station (Batterham 1992). In both cases, the research was quickly translated into feeding practices, not only in Australia, but in the much larger North American and European industries.

Campbell later extended his research to the effects of sex, genotype and metabolic modifiers on growth, carcass composition and energy/protein requirements (Campbell 1988) before taking leadership positions in the pork production industry in Australia and the USA during the 1990s and early 2000s, and later, Directorship of both Pork CRCs (Table 4). His work on growth promotants, especially porcine growth hormone, was continued by Frank Dunshea at Werribee after his return from postdoctoral studies with Dale Bauman at Cornell University in the late 1980s. Dunshea's later research achievements included demonstration of the efficacy and effect on nutrient requirements of the β-agonist, ractopamine (Paylean®), in finishing pigs (Dunshea *et al*. 1998), and the development and commercialisation of an effective immunocastration technology (Improvac®) for male pigs (Dunshea *et al*. 2001). It is estimated that, currently, industry adoption of the latter technologies is ~45% and 75% respectively (D. D'Souza, pers. comm.).

Another important research achievement during the 1980s was the development and commercialisation of AusPig, a computer simulation model of amino acid and energy utilisation for pigs of different genotypes and in different nutritional or climatic environments (Black *et al*. 1986). Developed under the leadership of John Black from the CSIRO Prospect, this model incorporated much of the above-mentioned nutritional research findings of Roger Campbell, Ted Batterham and others, and became the basis for the Australian feeding standards for pigs (CSIRO 1987). The original biological model was later extended to include ration formulation software, an expert system to identify biological limitations to maximum growth and feed efficiency, and a linear program to optimise the sale of pigs and maximise profit of the enterprise (Campbell and Williams 2018). After its commercialisation in 1989, AusPig was quickly embraced by Australian and international agribusiness corporations, and successfully used as a strategic tool for making management changes to increase profitability. However, its intended use for day-to-day decision-making in commercial piggeries has not been widespread. The reasons cited by its inventor include its operational complexity, the number of accurately measured inputs required and inadequate monitoring of productivity gains (Black 2014).

In the final decades of the 20th century, Australian scientists also made important, practical contributions to the health and productivity of poultry. Studies during the 1970s and 1980s on the characterisation of unique Australian strains of infectious bronchitis virus, led by Rob Cumming at UNE, were important for the later development of efficacious vaccines (Klieve and Cumming 1988). Subsequently, leadership of research on molecular characterisation of these rapidly mutating viruses, and on the development and strategic use of vaccines was assumed by CSIRO researchers, initially based at Parkville and later at the Australian Animal Health Laboratory (AAHL; Ignjatovic *et al*. 1997).

The Poultry Research Foundation (PRF) at Sydney University was established in 1958 by Terry Robinson to attract funding and establish linkages with the poultry industry. The first postgraduate student supported by the PRF was Erol Best, who went on to make important contributions to genetic improvement of broilers with the Tegel company, later part of the Ingham Group. During the period being considered, the focus of the PRF was on nutrition, initially through the efforts of Charles Payne, and later, Derek Balnave and Wayne Bryden. These scientists made significant contributions to delineating the role of biotin deficiency in the aetiology of the fatty liver and kidney syndrome in broilers (Payne *et al*. 1974), the effects of heat stress on poultry nutrition (Balnave 2004), and the importance of amino acid digestibility in practical feed formulation (Bryden and Li 2010). Bryden and colleagues also elucidated the antinutritional properties of cereal phytates in broiler feeds (Selle *et al*. 2000), while Mingan Choct identified similar negative effects of soluble non-starch polysaccharides (NSP; Choct and Annison 1992). These findings led to the development of enzymes as feed additives to improve the digestibility and nutritive value of cereals that contain high levels of NSP and/or phytates (Selle *et al*. 2000; Choct 2006). This technology was widely adopted by the poultry feed industry during the 1990s, with significant benefit to broiler growth and feed efficiency. Choct would later become the CEO of two very successful Poultry CRCs based at UNE (Table 4).

The health sciences: new developments and old challenges

The late 20th century saw major changes in Australia's ability to deal with possible incursions of dangerous exotic diseases of livestock; the identification and characterisation of novel viral pathogens, including the lethal zoonotic Hendra virus; the culmination of 100 years of work to eradicate bovine tuberculosis; and ongoing efforts to combat chronic endemic diseases, such as worm infestation in sheep.

During the 1970s, there were growing concerns about the threat of exotic diseases to Australia's livestock industries, sparked by the detection of bluetongue virus in cattle in northern Australia in 1968, and the devastating effects of sporadic outbreaks of foot and mouth disease (FMD) in other parts of the world, including most of south-east Asia. These concerns were sharpened by the fact that Australia had very limited capacity for diagnosis of exotic diseases and, therefore, an inability to mount rapid responses to possible incursions. After numerous false starts, this ultimately led to the Federal Government's commitment in 1973 to build the AAHL at East Geelong, Victoria. Construction of the massive high-containment facility began in 1978 and cost $158 million by the time it was officially opened in 1985 (Snowdon 2007). The current cost of replacing the AAHL is estimated to be more than $1.2 billion (CSIRO 2018). The CSIRO laboratory is presently one of only four in Australia with the highest level of biosecurity (BSL4), enabling it to handle the most dangerous animal and human pathogens. Even more significant are its facilities, unique in Australia and internationally rare, for housing of and conducting research on species ranging from mice to horses and cattle under BSL4 conditions.

An important part of the AAHL's role has been to provide diagnostic support to Australia's network of state veterinary laboratories. Prominent among these is the NSW Department of Primary Industries' Elizabeth Macarthur Agricultural Institute (EMAI) at Menangle near Camden, which was opened in 1990. The recently refurbished EMAI has PC3 laboratories and animal facilities that make it second only to the AAHL among Australian facilities designed to protect Australia's livestock industries from existing and emerging diseases.

Even before it opened, the AAHL was embroiled in controversy over its expense and relevance to the protection of the livestock industries. An early and prominent critic was the eminent ANU immunologist, Bede Morris, who initially was concerned about diversion of scarce funds from Australian universities (Butcher 2000; Snowdon 2007). When it became clear that the building of the AAHL would go ahead, Morris and others, including his former student, Alick Lascelles, then Chief of the CSIRO's Division of Animal Health, switched their criticism to question the need for the AAHL to import live FMD and other exotic viruses for the development of diagnostics and vaccines (Courtice 1989). This stirred up an enormous controversy involving scientific, political and industry leaders, as well as the general public, as comprehensively documented by Bill Snowden, the inaugural OIC and later Chief of the AAHL (Snowdon 2007). As a result, to this day, the AAHL has not been allowed to import live FMD virus, and has been obliged to conduct its R&D offshore through the Global FMD Research Alliance (CSIRO 2018). Ironically, a key plank of Morris' argument was that the need to import live FMD virus quickly would be obviated by the advent of effective recombinantly derived vaccines, yet, almost 40 years later, inactivated full virus vaccines remain the mainstay of immunological protection against FMD (Mahapatra and Parida 2018).

Between its opening and the end of the century, the AAHL justified its existence by creating novel diagnostic techniques and vaccines, identifying new pathogens and conducting educational programs to train Australian veterinarians in the recognition of exotic diseases. For example, in 1992 it took the AAHL only 4 h to confirm an outbreak of avian influenza, compared with 5 days in 1985 (Snowdon 2007). Perhaps the Laboratory's most notable and publicised achievements during this period were the isolation and identification of several previously unknown, lethal paramyxoviruses carried by bats, including Hendra virus in 1994, Menangle virus in 1997 and Nipah virus in 1999. Hendra virus, so far found only in Australia, had killed several horses and two humans before being identified, while Nipah virus was responsible for the culling of 1.1 million pigs and the deaths of 105 people during an outbreak in Malaysia in late 1998 and early 1999 (Field *et al*. 2001).

Although the controversial nature of the AAHL's inception, construction and early operations tended to overshadow much of the ongoing research on endemic diseases in universities and state department laboratories, there were some important successes in this arena. Among these was the eradication of bovine tuberculosis (caused by infection with *Mycobacterium bovis*) from Australian herds in 1997 (More *et al*. 2015). Efforts to control tuberculosis had begun about a century previously, but eradication became a serious goal only after inception of the national brucellosis and tuberculosis eradication campaign in 1970. As noted by More *et al*. (2015), there are few international examples of the successful eradication of bovine tuberculosis, and Australia's achievement has had a substantial and enduring positive impact on animal health and welfare, especially in the northern cattle industry.

During the quarter century being considered, the incidence of anthelmintic resistance increased greatly in Australia, driving scientists to seek alternative means of countering the sheep industry's most costly chronic disease problem. These included integrated pest management (IPM) programs, such as 'Wormkill', released in 1984 after development by a collaborative team of scientists from the CSIRO and the NSW Department of Agriculture led by the CSIRO's Keith Dash (Barger 1997). Although successful in the short term, this and similar IPM programs unwittingly augmented selection for chemical resistance, particularly in the highly fecund and rapidly mutating barber's pole worm (*Haemonchus contortus*; Emery *et al*. 2016). This led to the evolution of more sophisticated, multivariate IPM programs, and investigation of other non-chemical strategies, including genetic selection for nematode resistance (Woolaston and Piper 1996) and vaccination against *H. contortus* (Emery 1996). As discussed in the next section, the latter approaches did not begin to bear fruit until after the turn of the century.

Australia's pastoral ecosystems include numerous plants that are absolutely or conditionally toxic to livestock, with effects that range from the rapid-onset mortality sometimes caused by *Pimelea* spp., to the chronic, antinutritional effects of tannins and other polyphenolic compounds that are relatively concentrated in many tropical and subtropical forages. Identification, cataloguing and, where possible, control of such plants was a major activity of the colonial Stock Branches that preceded the state departments of agriculture in the 19th century. During the latter half of the 20th century, the understanding of the chemical nature and development of strategies to prevent or treat the effects of a wide range of plant poisons were greatly advanced by scientists in the Biological Chemistry Section of the CSIRO's Animal Health Laboratory at Parkville, led by the distinguished toxicologist, Claude Culvenor. Much of this work, including that on pyrrolizidine alkaloids in plants, such as heliotrope (*Heliotropium europaeum*) and Paterson's curse (*Echium plantagineum*), and lupinosis and annual ryegrass toxicity, is summarised in chapters written by Culvenor (2000) and his close colleague, John Edgar (Edgar 2000), in a book primarily authored by Butcher (2000).

Notwithstanding the far-reaching importance of the above research, perhaps the most intriguing and novel example of successful Australian research to combat a plant toxin is that on the cytotoxic non-protein amino acid, mimosine, found in the otherwise valuable tropical tree legume, leucaena. This involved a long and often frustrating battle by the CSIRO scientist, Raymond Jones, to prove that ruminal inoculation of susceptible Australian ruminants with rumen liquor from resistant Hawaiian goats could protect them from leucaena poisoning (Jones and Megarrity 1986). After demonstrating such efficacy, Jones and his microbiologist collaborators isolated strains of the hitherto unknown rumen bacterium found to be responsible for the degradation of isoforms of dihydroxypyridine, the toxic metabolites of mimosine. Appropriately, the bacterium was later named *Synergistes jonesii* after its discoverer. This led to the development of effective strategies for preventing the toxic effects of a forage that has become an extremely valuable component of tropical and subtropical pastoral systems for beef cattle in northern Australia (Halliday *et al*. 2013).

Research on international development of livestock production

The awareness of the need and opportunity for Australia to become involved in research to solve problems of food production in developing countries grew during the early post-war years, influenced by the international perspective and experience of leaders such as Ian Clunies Ross, the CSIRO's CEO (1949–59) and RJ Noble, Director of the NSW Department of Agriculture (1940–59). Clunies Ross had travelled widely in Asia and other parts of the developing world before and after World War II, while Noble was significantly involved with the founding and early operations of the United Nations Food and Agriculture Organisation (FAO) soon after the war.

Later, national leadership, with a special focus on livestock development programs, was provided by Derek Tribe during and after his tenure at The University of Melbourne. Tribe's appetite for international development work was apparently whetted by his consultancy with FAO to conduct the East African Livestock Development Survey in 1965. Later, after stepping down as the Dean of Agriculture at The University of Melbourne in 1972, he led a taskforce to consider the need for an international livestock research centre to be based in Africa as part of the Consultative Group for International Agricultural Research (CGIAR) system. After a contentious gestation, this resulted in the creation of the International Livestock Centre for Africa (ILCA) at Addis Ababa, Ethiopia, in 1974. Among numerous other leadership roles, detailed by Falvey (2012), Tribe was the at times controversial Director of the Australian Universities International Development Program from 1980 to 1985, and the driving force behind the foundation in 1987 of the Crawford Fund for support of Australian engagement in research and education devoted to international agricultural development. The latter fund is named in honour of Sir John Crawford, the eminent agricultural economist and former Vice Chancellor of ANU, and is considered by Tribe's biographer to be an appropriate capstone to his subject's distinguished academic career (Falvey 2012).

During the 1970s, Australian research organisations were involved in several major international programs or projects involving (mostly) livestock production. One was the 'Better livestock for better living' project in which the CSIRO was contracted by the Australian Development Assistance Bureau (ADAB) to equip, maintain and provide research support for the new Centre for Animal Research and Development at Ciawi near Bogor in Indonesia for a period of 10 years from 1975 (CSIRO 2002). This involved the long-term secondment of experienced scientists, including Harry Wharton as OIC and Len Cook as Research Leader, and the research training of many Indonesian scientists in Australian postgraduate programs.

Another ADAB-sponsored project that ran from 1975 to 1980 was the 'Thai-Australia Highland Agricultural Project', the livestock component of which was led by a youthful Lindsay Falvey. The essence of the livestock work was to enable the conversion of hill tribesmen in northern Thailand from opium growers to beef cattle producers (University of Queensland 1981). This led to Falvey's award of a PhD from The University of Queensland and a career in management of consultancies on international agricultural development research, capped by his appointment as Dean of Agriculture, Forestry and Horticulture (later the Institute of Land and Food Resources) at The University of Melbourne (1995–99). Among other international activities, Falvey presently chairs the Board of the International Livestock Research Institute (ILRI) that was formed in 1994 by the amalgamation of ILCA and the International Laboratory for Research on Animal Diseases (ILRAD) in Nairobi.

Throughout the last quarter of the 20th century, Ron Leng from UNE made major contributions to improving the nutrition of ruminants in the tropics and subtropics in both Australia and the developing world. From the mid-1970s, he and his long-time American collaborator, Reg Preston, undertook numerous consultancies in Latin America, Africa and south-east Asia, with a particular focus on promoting the efficient utilisation of locally available feed resources. Much of their practical research and its theoretical basis is summarised in their oft-cited monograph, *Matching ruminant production systems and available resources in the tropics and sub-tropics* (Preston and Leng 1987).

In 1982, the Australian Centre for International Agricultural Research (ACIAR) was established as a statutory authority to commission and coordinate (but not conduct) research on agriculture and food production in developing countries through collaboration between Australian and local scientists. Although livestock production never was the highest priority for the Centre, it has funded many livestock projects over almost four decades that have involved numerous Australian scientists. Not surprisingly, many of these individuals came from Australian institutions with established programs in tropical and subtropical livestock production and pasture agronomy, such as The University of Queensland and the CSIRO. Key individuals include Barry Norton, Max Shelton, Ross Humphreys and Dennis Poppi from The University of Queensland, who worked mostly in Thailand and Indonesia (e.g. Shelton and Stür 1991; Syahniar *et al*. 2012), and Anthony Whitbread, Bruce Pengally and Andrew Ash from the CSIRO, who worked in eastern and southern Africa (e.g. Whitbread and Pengally 2004). Norton also played an important, long-term role in projects on goat production as part of the Thai-Australia Prince of Songhla University Project (TAPSUP) funded by AusAID from 1981 to 1993. More recently, he led a project on New Technologies for Improving Goat Production in Vietnam, funded by the Collaboration in Agricultural Research and Development (CARD) from 2004 to 2010 (Norton *et al*. 2009). For an informative summary of recent ACIAR-funded research on cattle health and production in Indonesia, Vietnam and China, readers are referred to the book, *Beef Production in Crop-livestock Systems*: *Simple Approaches for Complex Problems*, which includes a series of case studies authored by Australian animal scientists and their Asian collaborators (Winter 2011).

Another important area of work funded by ACIAR was that led by Peter Spradbrow at The University of Queensland on the development of a thermostable vaccine against Newcastle Disease virus in chickens, for use in developing countries (Bensink and Spradbrow 1999). This aspect of research on perhaps the most important poultry disease worldwide has been continued by Spradbrow's former colleague, Robyn Alders, at the University of Sydney (Alders 2014).

A new era for extension and agricultural education

The fluctuating industry fortunes cited above, and changing political attitudes to the public funding of private agricultural enterprises led to major changes in the nature, organisation and funding of extension programs conducted by the state agencies during the period in question. In most states, the management of previously integrated research and extension programs was separated, with unfortunate consequences for both scientific activities. These included further isolation of extension officers from the research process and sources of the information they were required to extend to industry clients, and reduced contact between researchers and their traditional conduits to industry feedback and opinion (Marsh and Pannell 2000).

The nature of extension activities also changed, with reduced emphasis on service to individual producers, and increased responsibility for delivery of government policies and projects (e.g. Russell *et al*. 2014). Other regular forms of communication with producers also changed significantly with cessation of the publication of monthly or quarterly journals or digests by state departments, mostly during the 1980s. This move initially was not popular with many recipients and their families, who found the new forms of information transfer, such as Agnotes, and later, the Internet, to be more impersonal and less engaging than the traditional format. In some states, such as Western Australia, there were deliberate efforts to increase state collaboration with agricultural consultants and other agribusiness personnel through delivery of 'train-the-trainer' programs (Fitzpatrick 2011), reinforcing an already established trend towards greater reliance on private sources of technical and financial expertise.

The 1980s also saw the end of state departmental responsibility for vocational education in agriculture. Most well established colleges of agriculture became Commonwealth-supported Colleges of Advanced Education, which, as part of the Dawkins reforms, were later amalgamated with university schools of agriculture. In some cases, such as at Gatton in Queensland, Roseworthy in South Australia, Wagga in NSW and, potentially, Dookie in Victoria, the latter has led to reinvigoration of university teaching of the animal sciences and livestock production. However, there has been a disappointing net loss in the availability and quality of post-secondary programs designed to meet the vocational needs of young people to acquire the practical skills needed for successful management of modern livestock enterprises.

For example, in 1983, the previously state-managed Victorian colleges were incorporated into the Victorian College of Agriculture (VCAH), which was taken over by The University of Melbourne in 1997. It soon became clear that the University was culturally and philosophically ill-fitted to effectively manage vocational education, and this responsibility was passed back to the state in 2005 (Falvey *et al*. 2017). An early casualty was the McMillan Rural Studies Centre in Gippsland, which had offered vocational training in dairy management since the late 1970s. Although some of this training continued to be offered with the support of industry and state funding, a long-term consequence has been a marked reduction in educational opportunities for would-be and existing practitioners of dairy farming, Victoria's most important agricultural industry.

The 1980s and 1990s also were difficult times for the university schools of agriculture, with declining enrolments due to multiple factors, including the increasing urbanisation of the population and pessimism about vocational prospects for agricultural graduates, particularly in the uncertain financial climate discussed above. Some institutions, such as UNE, attempted to address the problem by creating new 3-year specialist degree programs, including one in animal science, but this strategy initially had only limited success (Godwin 2007). Another long-established degree program, offered by the University of New South Wales' School of Wool and Pastoral Science, was forced to close in 1997 because of low enrolments (Kennedy 2010).

The 21st century: early achievements and future opportunities and challenges

The first couple of decades of the new millennium have been momentous for the Australian livestock industries, marked by a severe, widespread and prolonged drought, related contraction of the dairy sector, continued restructuring of the sheep industry, and, more recently, resurgent markets for red meat and wool. There have also been some significant scientific achievements and changes in the nature of RD&E in support of animal agriculture. This section will highlight several of the latter, with particular emphasis on work relevant to multiple species and industry sectors, as well as briefly considering likely future challenges and opportunities for Australian livestock producers and the scientists working on their behalf.

New collaborative structures: the National Primary Industries RD&E Framework and the post-CRC era

In 2009, the Primary Industries Ministerial Council (PIMC) endorsed the National Primary Industries RD&E Framework that had been developed and proposed by the RD&E Subcommittee of the Primary Industries Standing Committee (PISC). Parties to the Framework included the federal and all state governments, the CSIRO, the universities, the RDCs and industry peak bodies. The overarching goal of the Framework was to encourage cooperation between science agencies and industry to enhance the efficiency and effectiveness of national agricultural RD&E capability (Australian Government 2011). A central operating principle was to rationalise, coordinate and integrate specific capabilities serving different industry sectors and cross-sectoral needs via encouragement of 'national R with regional D and local E'. The overall Framework spanned 14 industry sectors, including beef, dairy, pork, poultry, sheep meat and wool, and eight cross-industry sectors of which animal biosecurity and animal welfare were most relevant to the livestock industries. Primary and secondary responsibility for sector-specific research was assigned to different states with the expectation that states would also discontinue research in areas for which they did not have such a prominent role.

The process was vigorously championed by state agency representatives on the PISC RD&E Subcommittee, especially its Chair, Bruce Kefford, Deputy Secretary of the Victorian Department of Primary Industries. In hindsight, it is clear that the Framework, while praiseworthy in concept and aspiration, best served the interests of state jurisdictions that wished to rationalise their research portfolios. The CSIRO, for which the author often was a substitute representative on the RD&E Subcommittee, was an acquiescent, but more muted participant, whereas the universities were generally underrepresented and less enthusiastic than the other participants, notwithstanding formal commitment to the process by the Australian Council of Deans of Agriculture. At the time of writing, activities of the beef, sheep meat and poultry sectoral groups appear to have lapsed; whereas others, such as dairy and pork, have been subsumed by parallel industry planning processes. However, the cross-sectoral Framework for Animal Welfare has continued to act as a national forum and facilitator of research collaboration across species and industry sectors, while the Framework for Animal Biosecurity has been sustained through sponsorship and coordination by Animal Health Australia.

As summarised in Table 4, by the end of 2019, all CRCs based on the livestock industry sectors will have been wound up, with no immediate prospect of further renewal. Thus, a major issue facing research and industry partners is how to sustain successful collaborations into the post-CRC future without the 'carrot' of additional government funding. After cessation of the Poultry CRC in 2016, the meat and egg industries responded by forming Poultry Hub Australia. Although this organisation appears to have helped sustain communication between the research community and industry, and has supported educational programs, its success in supporting research collaborations is less clear. Another model that has yet to be fully tested is the recent fostering by MLA of strategic partnerships among red meat research providers. So far, these partnerships include the

National Livestock Genetics Consortium, the Animal Welfare Strategic Partnership and the Livestock Productivity Partnership. Much of the industry funding for the latter groups is being provided by the MLA Donor Co. rather than levy funds, which requires significant co-investment of cash by the research providers. This raises a question about sustainability, especially when the currently buoyant markets for red meat suffer an inevitable downturn.

Genetics and genomics

The success of LAMBPLAN during the late 1990s and early 2000s encouraged AGBU scientists, led by Daniel Brown, to develop a similar, BLUP-based approach to the genetic improvement of wool production in Merinos, despite the continued resistance of some industry leaders to the rigorous use of objective measures of wool quality traits. The outcome was MERINOSELECT, launched in 2005, which, by 2017, was estimated to be providing ~50% of rams and 80% of semen sold to commercial Merino breeders in Australia (Rowe 2018). A highlight of the latter report was its illustration of the continuing strong growth in adoption of MERINOSELECT compared with static numbers of non-adopters.

During the early 2000s, Australian animal scientists were prominent contributors to the large, international consortia that sequenced the bovine (Bovine Genome Sequencing and Analysis Consortium *et al*. 2009) and ovine (Jiang *et al*. 2014) genomes. The important contributions of CSIRO scientists were enabled by strong leadership from Shaun Coffey, Chief of CSIRO Livestock Industries, often against opposition from within and outside his organisation. Excitement in the research community generated by these successes led to optimism about early benefits to industry, both for genetic improvement and non-genetic management applications. Initially, successful commercial application was limited to the development of DNA markers for genes of major effect, such as the calpain–calpastatin system that underpins meat tenderness (Johnston and Graser 2010). Subsequently, there was progress in the translation of the new genomic information into applicable tools for genetic selection of complex traits (Wray *et al*. 2013). Australian authors of the latter paper included Mike Goddard FRS and his protégé, Ben Hayes, who have become international leaders in the development of genomic selection methodologies (Meuwissen *et al*. 2001) and their application to the genetic improvement of livestock.

Not surprisingly, the adoption of genomic selection has been most rapid in the dairy industry because of the ease with which accurate phenotypic data on production and health can be obtained and the dominance of a single breed, the Holstein (Hayes *et al*. 2009). For the more extensively managed and genetically diverse beef and sheep industries, the problem of phenotypic validation is being addressed by the creation of reference herds and flocks that are representative of the major breeds and production environments, and will allow genotyping and phenotyping of large numbers of animals, particularly for hard-to-measure traits (e.g. van der Werf *et al*. 2010). The genomic information is being incorporated into estimated breeding values alongside pedigree and performance information in selection tools, such as BREEDPLAN, LAMBPLAN and MERINOSELECT. Eventually, it is likely that genomic data will replace traditional pedigrees as a more accurate and rapidly obtained source of information on genetic relatedness (e.g. Boerner *et al*. 2015).

Australian efforts during the 1990s to create transgenic sheep were partly successful, but hampered by inefficient technologies for transferring novel DNA, unanticipated animal health problems and negative public reaction (Bawden *et al*. 1998; Adams and Briegel 2005). More recently, Poultry CRC researchers at the CSIRO AAHL have used direct *in vivo* transfection of avian primordial germ cells to generate stable germ-line transgenic chickens (Doran *et al*. 2018). This has enabled them to specifically mark the sex-determining chromosome, thereby identifying unwanted male birds *in ovo* and addressing the industry priority to abolish the practice of massive post-hatch culling of male chicks.

Reproductive efficiency and early influences on later productivity of offspring

Neonatal lamb mortality has long been recognised as a major source of reproductive wastage in the Australian sheep industry. Despite much useful research to address this problem during the latter half of the 20th century (e.g. Alexander 1984), poor markets and rising labour costs were significant disincentives to the adoption of this work by the wool industry. However, recent restructuring of the sheep industry away from wool in favour of prime lamb production, the drastic decline in the size of the national flock, and favourable markets for both commodities have changed producers' appetite for investment into improvement of lambing and marking percentages. Another important driver for this attitude is increasing public awareness and perception of lamb mortality as an animal welfare problem (Schmoelzl *et al*. 2015). A recent re-appraisal of the scale of the problem and opportunities to improve survival rates confirmed the central importance of lamb birthweight as a predisposing influence, and raised the possibility that the incidence of dystocia may have been an underestimated factor (Hinch and Brien 2014). These authors also commented on possible options for genetic improvement of specific traits underlying predisposition to mortality rather than relying on lamb survival as a maternal trait because of the latter's multifactorial nature and low heritability.

Reproductive performance has also been identified as a major limitation to productivity of the northern, Brahman-based beef herd, with high rates of calf mortality and low pregnancy rates in second calf heifers being of special concern (McGowan *et al*. 2014). This and other surveys have sparked wide-ranging investigations of possible contributing factors, including genetics (Johnston *et al*. 2014), nutrition (Dixon *et al*. 2011) and behaviour (Finger *et al*. 2014), as well as the development of innovative tools to remotely monitor extensively managed breeding herds (Stephen *et al*. 2018). However, it is too soon to gauge the likely adoption of these research outcomes and their impact on reproductive performance of the northern beef industry.

Australian scientists had long been aware that environmental insults, such as undernutrition during pregnancy, can have long-term consequences for postnatal development and productivity of offspring in livestock species. However, renewed interest in this concept was stimulated by exposition of the 'prenatal origins' hypothesis by the English epidemiologist, David Barker, in the late 1990s (Bell and Greenwood 2016). In possibly the first translation of these principles into applicable livestock management practices, scientists from DAFWA, led by Chris Oldham, and the Department of Primary Industries, Victoria, led by Andrew Thompson, undertook the Lifetimewool Project at two sites in Western Australia and Victoria involving the nutritional treatment of 3000 ewes over a period of 2 years, and subsequent observations of wool production and other traits of their progeny over three to five shearings. These researchers clearly demonstrated that realistic levels of supplementary feeding of Merino ewes to avoid weight loss during pregnancy can cause significant and permanent increases in fleece weight, and, to a lesser extent, decreased fibre diameter of their progeny's wool (Thompson *et al*. 2011). They also showed that identification and supplementary feeding of twin-pregnant ewes in late pregnancy completely removed any long-term penalty in wool production of twins. The positive impact of this outcome on the overall profitability of the wool enterprise was further enhanced by a concomitant improvement in survival of twin lambs born to supplemented ewes (Hocking Edwards *et al*. 2011).

Undernutrition of pregnant and/or lactating beef cows was shown to have negative effects on the growth of their calves to weaning and finishing in Beef CRC studies conducted by Paul Greenwood and his colleagues during the early 2000s (Greenwood *et al*. 2006). However, these reductions in weight at slaughter had few effects on carcass composition or meat quality characteristics that could not be explained by live or carcass weight (Robinson *et al*. 2013).

Meat science: enhancing value and strengthening the supply chain

In the early 2000s, the resurgence of the prime lamb industry, assisted by LAMBPLAN and market development initiatives, encouraged Australian meat scientists to extend the MSA program to include sheep meat as well as beef. Much of the underpinning research was conducted by the Sheep CRC, involving a national collaboration led by David Pethick from Murdoch University and strong financial support from MLA. The success of this work is indicated by the fact that in 2017–18, over 6 million sheep were processed through MSA pathways and standards, accounting for 26% of the national lamb slaughter and representing a 6-fold increase since 2010–11 (Meat & Livestock Australia 2018c).

A more recent meat science initiative has been the development of a major national project on advanced measurement technologies for globally competitive Australian meat (ALMTech), initiated in 2016 and supported by funding from the federal Rural R&D for Profit program in partnership with RDCs, meat processing companies, state departments and universities. This national project is led by Graham Gardner from Murdoch University, and its overarching goal is to provide beef, sheep and pig producers with access to more accurate descriptions of the key attributes that affect the value of their livestock: carcass lean meat yield, eating quality and compliance with market specifications. This is being undertaken by the refinement of existing technologies, such as dual-energy X-ray absorptiometry (DEXA), and the development of new tools, such as 3D imaging, for objective measurement of carcass and meat quality attributes, and, where appropriate, automation of abattoir procedures. Importantly, this project is enabling the transitioning of Sheep CRC work on meat quality and supply chain development after the CRC winds up in mid-2019. Already, some important research objectives have been achieved, including validation of improved DEXA systems for online measurement of lean meat yield in lamb abattoirs. However, it is too early to assess the overall achievements, including likely industry adoption and impact.

One Health: protecting the livestock industries and human health

During the past decade, Australian scientists at the CSIRO AAHL, state veterinary research laboratories and university veterinary schools have embraced the concept of 'One Health' to combat infectious diseases, and promote optimal health for humans, livestock and the environment. For those with a primary responsibility for the health of livestock and other non-human animals, this endeavour has focused on existing zoonotic pathogens, such as the Hendra and Nipah viruses, as well as on animal viruses with the potential to infect humans, such as avian influenza. Much research has continued to address the prevention and containment of dangerous exotic pathogens, such as FMD.

The AAHL's identification of the Hendra virus in 1994 was followed by almost two decades of intensive research and development that culminated in the commercial release of an efficacious equine vaccine in 2012. This work involved the collaboration of AAHL scientists, led by Deborah Middleton, with recombinant vaccine developers at Pfizer Animal Health and two USA biomedical research organisations, the Uniformed Services University of the Health Sciences and the Henry M. Jackson Foundation for the Advancement of Military Medicine (Middleton *et al*. 2014). Such extensive collaboration to address a dangerous threat to the health of both humans and livestock (in this case, horses) has been touted as an example of the application of 'One Health' principles, employing AAHL's nationally unique capacity for testing both model species and the intended target species under BSL4 conditions. However, much remains to be done to address the third pillar of the 'One Health' concept, environmental health, in such approaches to combatting infectious diseases.

Scientists at AAHL have also used transgenic approaches, similar to those described above to identify male chicks *in ovo*, to insert antiviral or immunological transgenes that target the avian influenza virus (Looi *et al*. 2018). However, even the positive human health implications of this approach to creating influenza-resistant birds have yet to overcome the economic, environmental, societal and legislative barriers to its commercialisation. Therefore, these authors have suggested that a more feasible approach may be to use genome-wide association studies of resistant and non-resistant birds to select for resistant genotypes and/or identify key genes for genetic restoration (Looi *et al*. 2018).

Australia's national network and systems for responding to an exotic disease incursion were severely tested by an outbreak of equine influenza first detected in Sydney in August 2007. The disease spread rapidly throughout north-eastern NSW, at peak infecting 47 000 horses on almost 6000 properties (Webster 2011). An aggressive program of rapid diagnosis, isolation of infected horses, restriction of movement and strategic vaccination, led by the NSW Department of Primary Industries, resulted in the eradication of the disease within 6 months, thereby vindicating the pre-existing Australian Veterinary Emergency Plan (NSW Department of Primary Industries 2008). The outbreak caused much angst within the thoroughbred and other horse industry sectors, as well an official enquiry into the national quarantine system. Although the incursion itself was cause for grave concern, the robust and effective response was reassuring, and the nation should be grateful that it was tested by such a highly infectious, but relatively benign, pathogen.

On the endemic disease front, a recent major breakthrough has been the successful development and commercial release in 2014 of a vaccine against *H. contortus*, Barbervax™ (Emery *et al*. 2016). Much of the lead-up research on this vaccine was undertaken at the Moredun Research Institute in Scotland, using a native subunit antigen prepared from worms harvested *ex vivo*, as proposed by parasitologists at the CSIRO Armidale (Le Jambre *et al*. 2008). Field evaluations of its efficacy against Australian strains of *H. contortus* were led by Brown Besier from DAFWA (Besier *et al*. 2016), and culminated in the establishment of a commercial production enterprise in Albany, Western Australia. Initially registered for use in sheep only, the vaccine may also be used in goats with veterinary approval and supervision.

Animal welfare

The late 1990s and early 2000s saw considerable growth in numbers and research productivity of Australian groups devoted to animal welfare and its underpinning scientific disciplines. Notable among these has been the Animal Welfare Science Centre (AWSC), initially a coalition of Victorian scientists from The University of Melbourne, Monash University, and the Victorian Department of Natural Resources and Environment. The AWSC was established in 1997, and until 2017 was led by Paul Hemsworth, an international expert on pig behaviour with joint appointments at The University of Melbourne and the Victorian Department of Natural Resources and Environment and its successors. Other prominent AWSC scientists included Graeme Coleman and Alan Tilbrook from Monash University, and John Barnett from The University of Melbourne. Membership has changed somewhat with the departure of Monash University in 2012, and the addition of the University of Adelaide and the South Australian Research and Development Institute (SARDI) to form a South Australian node in 2015. Reflecting the expertise of its leaders, the AWSC has had a focus on the pig and poultry industries. Among the Centre's recent successes has been its Pork CRC-sponsored research on optimisation of the group housing of pregnant sows to minimise aggression and injuries, and ensure adequate feed access for all animals (Stevens *et al*. 2015). This work was important and highly relevant because of the Australian industry's commitment to phase out the use of gestation stalls by 2017.

Animal welfare RD&E has also become a priority for the beef, sheep and dairy industries in recent decades. The dependence of Australia's pastoral industries on long-haul land transport has led to research on reducing stress and injury of beef cattle and sheep during transport, particularly by CSIRO scientists from the FD McMaster Laboratory at Armidale (Fisher *et al*. 2009). This important work has informed the development of policy and guidelines for land transport of these species in Australia (Australian Government 2012*b*), as well as demonstrating the benefits of reduced preslaughter stress for meat quality (Ferguson and Warner 2008).

Undoubtedly, the most vexatious recent issue facing the wool industry is the need to phase out the painful practice of mulesing without substantially increasing the incidence of or cost of treating flystrike in Merino sheep. Among numerous non-surgical alternatives that have been tested, only the so-called clip treatment to cause ischaemia in and allow removal of clamped breech skin has shown some promise. However, although this procedure is less painful than mulesing, it is not nearly as efficacious. Thus, a recent reviewer has concluded that the most sustainable approach to managing breech flystrike in the Australian Merino will be long-term (at least 10 years) genetic selection for plain breeches combined with a strategic IPM program (Fisher 2011). Such an approach has been used successfully by numerous progressive wool producers around Australia, in some cases for many years, and current genetic research is showing promising results (Bird-Gardiner *et al*. 2014). Nevertheless, a significant proportion of producers, including some influential industry leaders, seem unwilling to consider a future without mulesing, despite mounting threats to their social licence to operate.

Lameness in dairy cows is an ongoing international problem that, in addition to being a significant welfare concern, is associated with reduced productivity due to impaired fertility, decreased milk production, and increased treatment costs and incidence of enforced culling. Most international research on lameness has focused on full confinement systems in the northern hemisphere. However, recent surveys have highlighted the incidence of this problem on Australian pasture-based farms where cows often have to walk long distances on hard laneways and then stand in concrete-floored yards while waiting to be milked (Beggs *et al*. 2015; Ranjbar *et al*. 2016). The latter study also found that, in general, farmers greatly underestimated the incidence of lameness in their herds compared with that detected by the use of an objective lameness scoring system by trained observers. This finding was confirmed in a recent study involving >19 000 cows on 50 farms, which also observed that, contrary to expectation, lame cows were not necessarily among the last to be milked, highlighting the need for lameness scoring of all cows in the herd (Beggs *et al*. 2019). This finding is consistent with extension advice provided by Dairy Australia (Dairy Australia 2016).

Another important welfare issue confronting the Australian dairy industry is the treatment of ~400 000 bobby calves born each year. Systematic research on the effects of road transport and feed withdrawal on these young animals (Fisher *et al*. 2014) has contributed to clear industry guidelines for their humane treatment (Dairy Australia 2019). However, the issue remains a potentially major risk to the dairy industry's social licence, and scientists continue to seek more acceptable long-term solutions. One of these could be to develop more effective production systems and markets for red veal, as opposed to milk-fed white veal produced in confinement systems that are illegal in Australia. However, considering the present lack of consumer enthusiasm for red veal, a more satisfactory solution could be to greatly reduce the number of male calves born through use of sexed semen and, possibly, extended lactation programs, as proposed by Borman *et al*. (2004). Widespread adoption of such an approach will require the development of more effective and less expensive technologies for the production of sexed semen than that presently available, and further research into the feasibility of extended lactation in Australian dairy management systems.

Environmental issues

Increased public awareness and concern about the environmental impact of animal agriculture in Australia, coupled with growing industry appreciation of the importance of environmental stewardship and sustainability, has led to considerable RD&E on several fronts during the past 20 years. These have included: long-term investigations of grazing management in tropical rangelands to optimise the balance between sustainability and profitability; assessment and mitigation of enteric emissions of the potent greenhouse gas (GHG), methane, principally from ruminant livestock; and life cycle analysis of GHG emissions and water use in various livestock production systems.

The Wambiana grazing trial was established near Charters Towers in 1997 to test the ability of different beef cattle stocking strategies to cope with climate variation in a tropical savannah environment. Results over a period of 20 years have conclusively demonstrated that fixed, moderate stocking rates at long-term carrying capacity, with or without spelling, maintain pasture condition, maximise individual animal production and are twice as profitable as fixed, heavy stocking (O'Reagain *et al*. 2018). This long-term trial represents an excellent example of collaboration between scientists led by Peter O'Reagain from the Queensland Department of Agriculture and Fisheries, the highly supportive Lyons family who own and manage 'Wambiana', and several funding bodies, especially MLA. It also is notable for its successful blending of innovative research, practical development and effective extension, particularly through demonstration activities.

According to the latest Australian National Greenhouse Accounts (Australian Government 2018), enteric methane, mostly emitted by ruminant livestock, accounts for ~9% of Australia's total GHG emissions. The validity of this estimate is supported by considerable research by Australian scientists, particularly during the past decade or so, initially stimulated by the prospect of Federal legislation to create a carbon trading scheme or introduce a carbon tax. A recent, notable achievement has been the derivation of a universal equation to predict methane production of forage-fed cattle in Australia (Charmley *et al*. 2016; Fig. 4). This stemmed from a combination of the results of several groups that used the gold standard technique of respiration calorimetry to measure methane production, and relate it to dry matter intake in dairy and beef cattle fed temperate forages and beef cattle fed tropical forages. Most significantly, application of this equation to the methodology used to calculate Australia's national inventory has reduced previous, less direct and comprehensive estimates of GHG emissions from forage-fed cattle by 24%, representing 12.6 Mt CO_2-e per year.

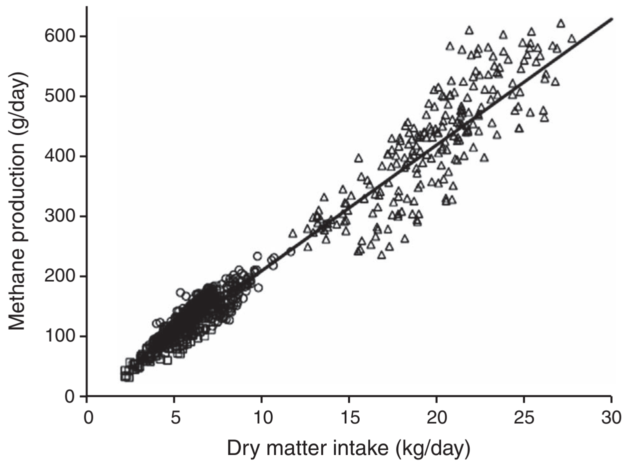

Fig. 4. The combined relationship between methane production (CH_4) and dry matter intake (DMI) for dairy (open triangles), southern beef (open circles) and northern beef cattle (open squares). The fitted line represents the relationship: CH_4 (g/d) = 20.7 (±0.28) DMI (kg/day); ($R^2 = 0.92$, $P < 0.001$). Reproduced from Charmley *et al*. (2016), with permission from CSIRO Publishing.

The several groups involved in this work have also been active in evaluating feeding practices and other means of mitigating emissions from individual animals. For example, Peter Moate and his colleagues at the National Centre for Dairy Research and Development at Ellinbank, Victoria, have demonstrated efficacious responses to supplementation of dairy cows with various feed sources of lipid and/or tannins (Moate *et al*. 2011; 2014). Among a wide range of tropical grasses and legumes tested by Kennedy and Charmley (2012), the nutritious perennial browse legume, leucaena, was unique in significantly reducing methane yield in Brahman beef cattle, possibly due to its higher tannin and/or lipid content. The Ellinbank group was also collaboratively involved in perhaps the most promising work on methane abatement to date. This research, led by scientists from the Pennsylvania State University, found a persistent 30% reduction in methane emissions without effect on milk production of high-yielding dairy cows fed the methane inhibitor, 3-nitrooxypropanol (Hristov *et al*. 2015).

Approaches to mitigation of methane emissions of individual animals, such as those discussed above, may have a place, especially in the more intensively managed dairy industry. However, for pastoralists and the scientists supporting them, focusing on emissions intensity (i.e. methane emitted per unit of meat, milk or wool produced) should offer greater scope and incentive to change management practices, because reductions in intensity almost always are associated with increased productive efficiency and can be achieved by many different management strategies. Thus, life cycle analysis of factors influencing changes in GHG emissions intensity of Australian beef production between 1981 and 2010 showed that higher weaning rates, faster growth rates, heavier carcass weights and lower mortality rates all decreased emissions intensity, as well as increasing production efficiency (Wiedemann *et al*. 2015). Similarly, it was shown that factors increasing the efficiency of production of export lamb also reduce GHG emissions intensity (Wiedemann *et al*. 2016). A counter argument is that increased productive efficiency may lead an individual enterprise or industry sector to increase herd or flock size and thereby increase total emissions regardless of improvements in emissions intensity. However, this argument ignores the fact that agricultural emissions are a global issue and that, ultimately, the need to efficiently satisfy the global demand for food must be balanced against the need to reduce total GHG emissions. Thus, in future, it seems likely that both efficiency of resource use and carbon footprint (i.e. emissions intensity) will become bargaining chips in international food trade negotiations.

Life cycle analysis has also been used to estimate water use for beef production in Australia between 1981 and 2010. During the 5 years to 1985, water use was estimated to average 1465 L/kg liveweight, falling to 515 L/kg liveweight during the 5 years to 2010 (Wiedemann *et al*. 2015). Management factors contributing to this reduction included an increase in use of grain finishing, intensification of land occupation and the major reduction in use of irrigation for pasture finishing in southern Australia. The fact that almost all Australian cattle feed is now produced in dryland systems must contribute to the above estimates of water use being considerably lower than similarly estimated North American values. Other methodological considerations, such as how to account for rainfall usage in non-arable dryland systems, apply to estimates of water usage for beef (Wiedemann *et al*. 2015) and lamb (Wiedemann *et al*. 2016) production in Australia.

Extension services, technology transfer and adoption of new practices

As briefly discussed in the previous section and analysed by Marsh and Pannell (2000), by the end of the 20th century, trends in the contraction of publicly funded agricultural extension, and increased roles for individual private consultants and agribusinesses were apparent. These trends have continued in the subsequent two decades, albeit at different rates among industry sectors and state jurisdictions. For example, the employment of private consultants and advisors from seed/fertiliser companies by broad-acre crop growers far exceeds the use of consultants and corporate sources of advice in the extensive pastoral industries. In Western Australia, the role of DAFWA in extension, beyond publication of fact sheets and maintenance of websites, has essentially vanished, whereas in the eastern states, especially NSW, state agencies have continued to employ extension specialists in support of the major industry sectors.

Several times in this article, Australia's traditional reliance on state departments of agriculture to provide extension services has been questioned, especially in relation to the reluctance of universities to become involved in this activity. However, there are at least a couple of recent exceptions to this situation, as well as one of longer standing. The latter is The University of Melbourne's McKinnon Project, founded by Fred Morley in 1983 to conduct education, applied research, and whole-farm consultancy for the sheep and beef industries in southern Australia (Hunt *et al*. 2014). The Project has been successful in promoting and strengthening linkages between researchers, consultants and producers, including participatory research and demonstration activities. However, its broader applicability as a model for university participation in extension is restricted by its focus on a relatively small number of producer clients on a fee-for-service or subscription basis.

A second model is the Tasmanian Institute of Agriculture (TIA), which is a joint venture between the University of Tasmania and the Tasmanian Department of Primary Industries, Parks, Water and Environment (DPIPWE). Initiated in 1997, the TIA incorporated former DPIPWE extension staff in 2009, making it the only Australian institution to resemble the USA Land Grant University system (Hunt *et al*. 2014). Thus far, government, university and industry bodies appear to have been supportive of the TIA. However, the organisation is facing challenges, including maintenance of funding and overcoming cultural barriers to the integration of staff not totally committed to the 'pure' academic pursuits of in-house teaching and research.

The third example is the Queensland Alliance for Agriculture and Food Innovation (QAAFI), founded in 2010 as a partnership between The University of Queensland (UQ) and the Queensland Department of Agriculture, Fisheries and Forestry (QDAFF). Operating as a UQ research centre, QAAFI receives funding directly from the state government to cover the salaries of former QDAFF senior researchers transferred to become employees of UQ. Unlike the TIA, its direct responsibilities do not include extension for which there is tacit reliance on historical relationships between the former QDAFF research officers and their extension colleagues still in the department. Thus far, this informal arrangement appears to have worked fairly well, but, with personnel changes within both QAAFI and QDAFF, and different measures and expectations of achievement in the two organisations, these relationships seem unlikely to be sustainable.

The likely proliferation and increasing extension role of private consultants and agribusiness personnel raises several questions: (1) How will the expertise and related activities of these multiple providers be coordinated without wasteful overlap and unnecessary competition, in a manner that is transparent and useful to producers? (2) How will these providers be connected to the R&D community that is the source of new technical information and other research findings? (3) Who will train the trainers? In answer to these questions, it is assumed that state agencies will not have future responsibility for extension leadership beyond the need to maintain ongoing commitments to public benefit functions, such as biosecurity, product integrity and environmental protection. The question of coordination could be addressed by the creation of a professional accrediting system, management of which could be funded by relevant RDCs. This could involve the awarding of credits for participation in professional development activities and management of a register of qualified individuals. Responsibility for addressing the remaining two questions should mostly lie with the universities and, to some extent, the CSIRO, recognising that although the RDCs increasingly devote funding to extension and adoption programs, they do not have the in-house capability to do the actual work. Such use of industry funds to incentivise the universities would both address political concerns about using public funds for private good and help the universities to fulfil their aspirations for public engagement.

Future challenges and opportunities

Predicting the future is risky and almost certain to be inaccurate. For example, history shows that much of the important research described above was not anticipated or planned for in earlier decades. However, although the Australian livestock industries are likely to face presently unforeseen future challenges, others can be predicted with some confidence, based on events and trends referred to earlier in this article. Several of these are briefly discussed below, with emphasis on issues that should be amenable to scientific solutions. These include environmental sustainability, improvement of animal welfare, protection from exotic diseases, assurance of product integrity and increasing the profitability of livestock enterprises by enhancing total factor productivity. There will also be an increased need for animal scientists to objectively justify the contributions of livestock production to human well-being.

The challenge of climate change has several implications for livestock production. As discussed above, the contributions of livestock operations to GHG emissions will need to be accurately monitored and, where possible, mitigated or offset by management changes that reduce emissions and/or increase sequestration of GHGs. Reducing the methane emissions of individual ruminant animals should continue to be a research objective but, as argued above, greater emphasis should be placed on reducing emissions intensity through increased efficiency of production. Protecting livestock from the consequences of climate change by increasing their innate resilience and devising management strategies to minimise the effects of extreme weather events should also be a priority.

The social licence to operate livestock enterprises will come under increasing pressure from public scrutiny of management practices that, while presently tolerated, may be deemed unacceptable in the future. The scientific responses to this challenge should prioritise objective assessment of the physical and psychological well-being of stock and, whenever possible, replacement rather than mitigation of aversive practices. Examples of the latter will include immunological approaches to the castration of male and female animals in place of presently used surgical procedures, and application of molecular genetics to select for polledness and obviate the need for physical dehorning, particularly in *B. indicus* cattle. Genetic selection for resistance to flystrike in Merino sheep as an alternative to mulesing should also continue to be a major welfare research priority.

Australia has an enviable freedom from many of the notifiable infectious diseases that ravage livestock populations elsewhere. As discussed elsewhere (Bell *et al*. 2011), this increasingly will be challenged by expanding globalisation of trade, human spread into new habitats, increasing tourism and movement of cargo across national boundaries, climate change, a looming shortage of appropriately trained animal health professionals, and physical constraints to quarantine barriers. The export and domestic markets for food products of Australian livestock are also at continuous risk from food-borne pathogens that can enter the food chain at various points. This risk will be exacerbated by the increased scale, intensification, and complexity of on-farm operations and the post-farm processing and distribution chain, requiring increased research on rapid and accurate diagnosis of pathogens, and on product traceability through the entire food chain.

Recent slowing of growth in total factor productivity of Australia's livestock industries has raised concerns about the future profitability of livestock farming enterprises (Boult *et al*. 2018), notwithstanding presently favourable markets for red meat and wool. This report cited the importance of investment in RD&E as the main driver of long-term growth in total factor productivity, highlighting the ongoing need for research to promote productive efficiency by increasing production outputs and containing inputs of physical resources and labour. Among the numerous research opportunities, the application of genomic selection to achieve genetic improvement in production and health traits stands out, particularly for complex traits, such as disease resistance and reproductive performance, that have largely resisted progress via traditional quantitative genetic approaches. On the input side, a major opportunity is to reduce labour costs via development and application of remote sensing and management tools, particularly in the extensive pastoral industries (Leigo *et al*. 2012).

Some of the challenges and opportunities outlined above are multifactorial and intertwined. For example, reducing the incidence of neonatal mortality in the southern sheep flock and northern beef herd will address both a looming welfare issue and a major limitation to productive efficiency. Opportunities to achieve these goals will include the use of genomic selection to improve specific traits that underpin the broad maternal trait of lamb survival, as well as more effective extension and adoption of management practices based on the wealth of existing knowledge. An initial goal for research into northern calf mortality should be to develop tools to remotely monitor the place and time of calving, as well as factors such as postnatal maternal behaviour and incidence of predation, before effective intervention strategies can be developed.

Finally, there will be an increasing need for animal scientists to stay abreast of societal issues that have implications for the livestock industries and, when the opportunity arises, be willing to objectively engage in the public debate over such issues. A current example is the recent publication of a report by the EAT-*Lancet* Commission that proposes global action to drastically reduce human consumption of livestock food sources (Willet *et al.* 2019). Although the authors' concern for human and environmental health is laudable and some of their specific proposals have merit, the report contains many inaccuracies and misrepresentations that reveal both a lack of familiarity with the peer-reviewed scientific literature and a disturbing tendency to cite only research findings that support the authors' preconceived opinions. Failure to challenge this and likely future reports could have negative consequences for the shaping of political and public opinion similar to those created by the publication of the now-debunked *Livestock's Long Shadow* report in 2006 (Pitesky *et al*. 2009).

Conclusions

(1) Much of the success of the Australian livestock industries over the past 230 years can be attributed to the discovery, development, and extension of novel tools and practices by the scientific community, as well as their adoption, application, and, sometimes, improvement by ingenious and hard-working producers. This article has focused on the contributions of scientists working in Australia, many of whom have garnered international reputations for their research achievements. However, science is not confined by national boundaries, and it must be acknowledged that many of the achievements of Australian animal scientists would not have been possible without the foundations of research undertaken abroad.

(2) An initial focus on animal health during the 19th and early 20th centuries was followed by development of the core disciplines of nutrition, reproduction and, somewhat later, genetics, as well as animal behaviour and other disciplines that underpin research on animal welfare. Early successes in each of these individual disciplines has led to an appreciation of the importance of multidisciplinary approaches to large, complex problems, as fostered by the Cooperative Research Centres program over the past 30 years, and often augmented by integrative systems modelling. The ability to work in such an integrative environment, often involving multiple institutions, as well as individual and institutional flexibility and adaptability to new challenges and technologies, should be cornerstones of future planning for research capability to support Australia's livestock industries.

(3) It is the author's contention that, early in the development of institutions to support Australian agriculture, an opportunity was missed to integrate extension and continuing education opportunities for producers with student education and research in the universities. This resulted in the state departments of agriculture having almost exclusive responsibility for publicly funded extension, and culminated in an unfortunate administrative separation of extension from research, to the detriment of both functions. The present challenge is how to promote the integration of research, development and extension when the latter function is increasingly becoming the province of private consultants and agribusiness companies.

(4) It is ironic that public awareness of and concerns about perceived negative aspects of livestock production are increasing at a time when <2% of Australians are directly involved in the commercial production of food or fibre, and the great majority of the population are now at least a couple of generations removed from a family association with farming. This places great responsibility on leaders and scientific supporters of the livestock industries to communicate clearly and accurately on sometimes contentious issues with the general public and its policy-making servants.

Conflicts of interest

The author declares no conflicts of interest.

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