Characteristics and Perspectives of Disease at the Wildlife-Livestock Interface in Oceania

Simon Humphrys and Michel De Garine-Wichatitsky

Contents

Introduction

Oceania's thousands of islands result in a plethora of microhabitats, but can be broadly categorized into four geographical groups comprised of distinct island clusters from a geographical, cultural, and climatic perspective (Fig. 1). Melanesia, Micronesia, Polynesia, and Australasia consist of low-islands built from corals, high islands positioned along the ring of fire created through volcanic activity, and continental islands consisting of Australia, New Zealand, and West Papua/Papua

S. Humphrys
Animal Health Australia, Canberra, Australia
e-mail: SHumphrys@animalhealthaustralia.com.au

M. De Garine-Wichatitsky (✉)
ASTRE, CIRAD, INRAE, University Montpellier, Montpellier, France

Faculty of Veterinary Medicine, Kasetsart University, Bangkok, Thailand
e-mail: degarine@cirad.fr

J. Vicente et al. (eds.), *Diseases at the Wildlife – Livestock Interface*, Wildlife Research Monographs 3, https://doi.org/10.1007/978-3-030-65365-1_7

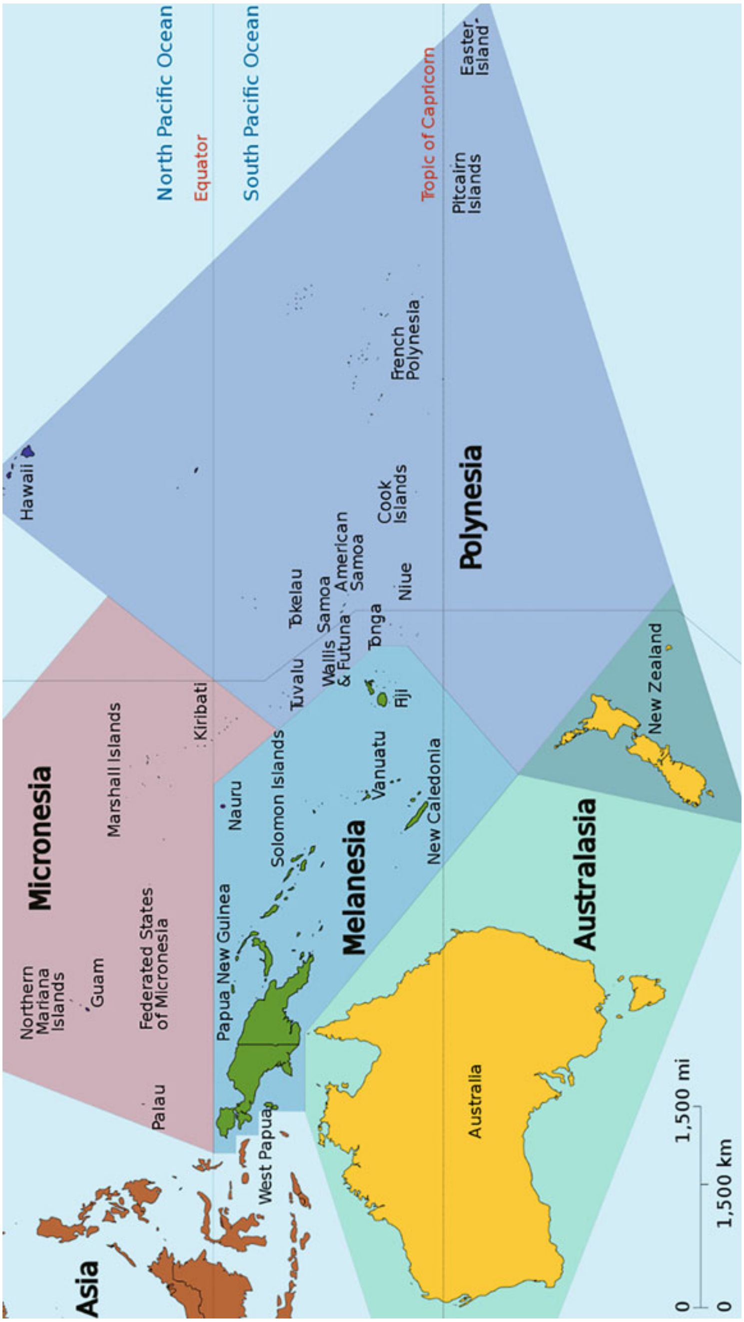

Fig. 1 Geographical grouping of regions comprising Oceania (Wikipedia)

New Guinea. While the central and western Pacific low and high islands have relatively uniform flora, fauna, and climates (sub-tropical and tropical), the continental islands exhibit far greater diversity of ecosystems, including arid deserts, Mediterranean habitats, temperate and tropical rain forests, alpine environments, mountainous plateaus, fiord lands, and sub-tropical savannas.

Oceania is also home to two of the 17 “megadiverse” countries on earth (Australia and Papau New Guinea; Shi et al. 2005), which refers to the world’s top biodiversity-rich countries measured by the total number of species and endemism at the species, genus, and family levels (McNeely et al. 1990). While being a megadiverse country does not involve a fauna criterion, a unique feature of the three continental islands’ (i.e., Australia, New Zealand, and Papua New Guinea) native fauna is the relative scarcity of placental mammals. Oceania is a continent of marsupials (macropods, possums, and dasyuromorphs), birds, reptiles, and insects that occupied many of the ecological niches placental mammals dominated elsewhere in the world. In Australia alone, 87% of mammals, 93% of reptiles, 94% of frogs, and 45% of birds are endemic and exist nowhere else on earth (Chapman 2009).

Humans have inhabited Australia, Papua New Guinea, and a number of the Melanesian Islands for tens of thousands of years, while a majority of the Micronesian and Polynesian Islands have been inhabited for 700–3500 years (Anderson 2009; Jupiter et al. 2014). European colonization of the continent has been relatively recent at less than 250 years (Flexner 2014). Micronesians, Melanesians, and Polynesians traditionally husbanded pigs and poultry prior to European arrival. The first European domesticated livestock (cattle, horses, sheep, goats, pigs, poultry) were introduced into Oceania within the last 300 years (Kiple 2007). Also, with English colonization came game species (deer, rabbits, hare) to Australia and New Zealand. From the small, self-sustaining family farms of a century ago to the present, the scale and efficiency of agricultural animal production principally across larger islands with the greater arable land area such as Australia, New Zealand and to a lesser extent Papua New Guinea and Fiji, has increased significantly with advances in mechanization, intensification, and improved animal genetics. These changes resulted in greater agricultural production scales where climate and land availability allowed natural capital to be modified to support livestock grazing or fodder production. The scale of this transformation also necessitated greater transportation of livestock through supply chains as they evolved to be more efficient and enterprises specialized to focus on specific segments of livestock production like breeding (studs), growing out (grazing/feedlots), transacting (sale yards), and processing (abattoirs). Transport of livestock across significant distances and presence on multiple properties demonstrated in Fig. 2 before being processed at an abattoir or live export facility exponentially increases the biosecurity risks of disease transmission from wildlife-livestock as well as livestock-livestock interfaces that need to be managed to maintain a robust animal health system.

Across the region, agriculture is pivotal to economic stability and contributes up to 30% of the national gross domestic product in some Pacific Island states (Stewart 2006), and livestock production is a significant agricultural sector in a majority of Oceania’s economies. While not generally realized as large producers, a number of

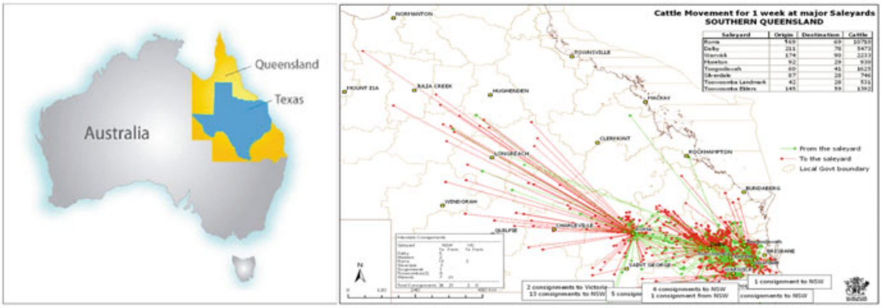

Fig. 2 An illustration of the extensive movement of 23,640 cattle through 8 sale yards in 1 week within southern Queensland, Australia's second-largest state by land area

Pacific Islands and territory countries (PICTs) have the highest pig and poultry densities in the world. Ten of the 22 PICTs rank in the top-25 countries globally for pigs/hectare of agricultural land area and 13 of the 22 PICTs rank in the top half of countries globally for poultry density (Brioudes 2016). For continental islands, the livestock sector also provides significant export revenues (Alexandratos and Bruinsma 2012). Almost at odds with the importance of agriculture, Oceania is a highly urbanized continent (Fig. 3), with a majority of the human population living in or near urban centers. The extremes in the region are Australia, which is quite developed, and Papua New Guinea, which retains a relatively low human density due in part to the majority of the population continuing to lead an agrarian tribal existence (Bourke and Harwood 2009; United Nations 2019). Australia's urbanization, coupled with its vast land area, results in expansive tracks of land where wildlife and livestock can intermingle in the absence of human intervention. A similar dynamic, although not to the same geographical extent, occurs in New Zealand, Papua New Guinea, and other islands across the region that can sustain extensive livestock production.

The scaling and stratification of livestock production systems that have occurred in Australia and New Zealand has not been possible for other countries within Oceania due to climate and land availability/type. These limitations, along with cultural imperatives, have resulted in the importation of processed livestock products for most of Oceania's countries being driven by human demand, much of which comes from Australia and New Zealand. Exportation of livestock and livestock products besides Australia and New Zealand is modest. The dynamic of inter-Oceania trade involving Australian and New Zealand livestock products being exchanged within regional island nations and highly regulated importation of livestock and livestock products from the rest of the world that is very limited in scale is one of this region's biosecurity advantages, irrespective of the wildlife-livestock nexus present across Oceania's livestock production systems.

The arrival of Europeans and the livestock/game species they brought with them to many PICTs also impacted native wildlife. Old World diseases (e.g., bovine tuberculosis, foot and mouth disease, rabies), land clearing for grazing,

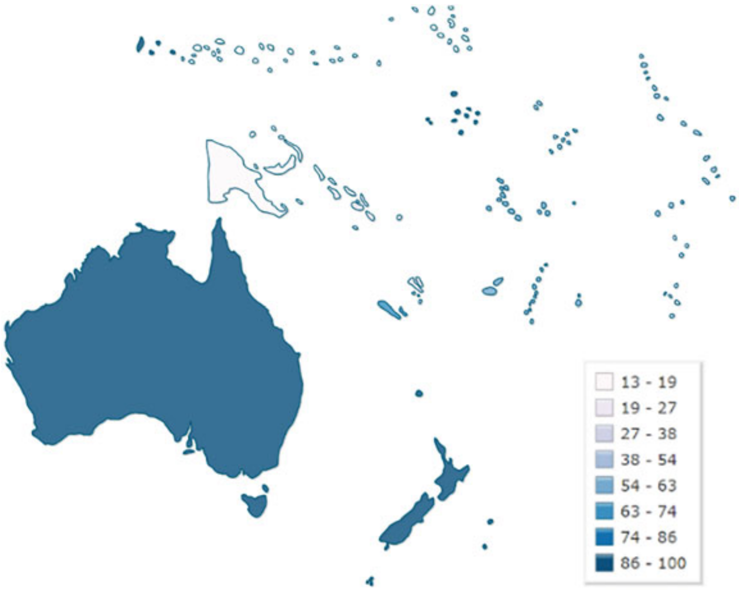

Fig. 3 The map below shows how urban population (% of total) varies by country in Oceania. The darker the shade, the higher the urbanization. The country with the highest value in the region is Nauru, with a value of 100%. The country with the lowest value in the region is Papua New Guinea, with a value of 13%. Source: The United Nations Population Division's World Urbanization Prospects

Fig. 4 Pictured are European rabbits in high densities decimating pasture ecosystems in Australia and New Zealand

overexploitation, and introduced species rapidly transformed landscapes (Jupiter et al. 2014; Kepple et al. 2014). This led to precipitous declines in native vegetation communities as well as pasture systems designed to support domestic livestock production. A good example of an introduced herbivore that can have devastating impacts on native plant populations is the European rabbit (*Oryctolagus cuniculus*; Fig. 4). Response to the agricultural and environmental threat posed by rabbits was the advent of government-led wildlife management, including research into disease as a biocontrol (e.g., myxomatosis and rabbit hemorrhagic disease). This effort took

Fig. 5 Pictured left panel are wild pigs near cattle in Australia and the right panel shows direct contact between brush-tailed possums and cattle in New Zealand

advantage of a disease-wildlife interface that fortunately (as researched) was specific to European lagomorphs and left Oceanic wildlife unaffected (Cook and Fenner 2002; Edwards et al. 2002).

While rabbit biocontrol has proven effective over the last 50 years, management at other wildlife-livestock interfaces has been less successful. Across Oceania, wild pigs (*Sus scrofa;* Fig. 5) and domesticated, free-ranging swine are noted vectors for the transmission of leptospirosis and brucellosis (Ridoutt et al. 2014; Guernier et al. 2018). In New Zealand, introduced brushtail possums (*Trichosurus vulpecula*) from Australia act as a secondary host that transmit bovine tuberculosis to cattle (O'Neil and Pharo 1995), akin to European badgers (*Meles meles*) transmitting the same pathogen (*Mycobacterium bovis*) to cattle in the United Kingdom (Hone and Donnelly 2008; Fig. 5). Both of these wildlife-livestock interfaces are nearly impossible to prevent in the extensive grazing systems that dominate livestock production in the continental islands or indeed in the more subsistence, free-range husbanding of livestock in the low and high islands of Oceania. This has resulted in entrenched endemic disease reservoirs on islands within Oceania for bovine tuberculosis and other bacterial diseases, including leptospirosis and brucellosis variants (Crump et al. 2001; Victoriano et al. 2009). Additionally, Hendra and Nipah viruses have become emergent in Oceania, which sporadically spill-over from native fruit bats (*Pteropus* spp.) into domestic horses and pigs and then into humans (Mackenzie 2005; Field et al. 2011; Fig. 6).

There is a continuum of biosecurity throughout Oceania, from little in free-ranging livestock, too highly organized, intensive raising of poultry, pigs, and cattle. The level of biosecurity in place depends on geographic location, species, and type of agricultural enterprise. In virtually all these scenarios there is opportunity for direct and indirect transmission of diseases between livestock and wildlife as they directly or indirectly share resources. While available evidence suggests that most, if not all, of Oceania's islands remain free of many of the most impactful diseases of livestock elsewhere in the world (e.g., foot and mouth disease, pestivirus, classical swine fever, highly pathogenic avian influenza; Brioudes 2016), maintaining disease-free status will require an enormity of investment to prevent pathogen

Fig. 6 A horse being tested for Hendra virus in Australia (left panel). Fruit bats are the primary host of Hendra virus (right panel)

entry, contain and eradicate diseases if pathogen entry occurs, and surveillance and monitoring to prove disease freedom or detect disease presence.

Socioeconomic and Biogeographical Drivers of the Wildlife-Livestock Interface

The first livestock introduced across the majority of Oceania's islands included pigs and poultry (chickens and occasionally ducks), which provided a valuable food source. Excess animals were usually traded with neighbors and occasionally seafaring visitors. Pigs and poultry were primarily free-ranging, and many went feral, leading to large and expanding populations across Melanesia and Polynesia (e.g., Hawaiian Islands). Like pigs, poultry traveled from southeast Asia with their human counterparts, based on genetic evidence (Storey et al. 2012). Poultry's main purpose was egg production, a protein source that could be kept for extended periods and did not require refrigeration. At this time, poultry meat was only occasionally eaten. Similarly, the original primary purpose of cattle was not as a source of meat either; cattle were primarily valued as beasts of burden that facilitated the cultivation of crops and as a source of leather.

Approximately 250 years ago, Europeans created a new livestock-wildlife interface across Oceania's largest land masses that has had a far more profound influence on their natural capital and civilizations. As Oceania's largest islands were settled by Europeans, socioeconomic aspirations and cultural considerations that were multigeneration old traditions in Europe drove a desire to replicate livestock husbandry practices in Australia and New Zealand. For example, Australia's livestock industry began in 1788 with the arrival of the first fleet of English settlers. The initial count of 7 horses, 7 cattle, 29 sheep, 74 pigs, 5 rabbits, 18 turkeys, 29 geese, 35 ducks, and 209 chickens (Australian Bureau of Statistics 2001) grew exponentially to the degree that Australia began exporting livestock. From that nucleus of livestock in the late eighteenth century, Australia became arguably the largest exporter of sheep and goat meat to global markets, and currently exports more than 70% of its beef production annually (Meat and Livestock Australia 2019; Eather 2020). The only contender to the mantle of greatest sheep meat exporter emanates from the mid-1800s when New Zealand became a pasture-fed livestock powerhouse of production, even exceeding Australia's sheep population in the 1980s. The ever-increasing land clearing and transformation of native vegetation to grazing land to support livestock and agricultural production has transformed Australian and New Zealand landscapes and not always for the better (Knight 2009; Bradshaw 2012; Kepple et al. 2014). Different breeds of cattle, pigs, sheep, goat, horses, deer, and poultry were imported with the intent of creating a domestic supply that ultimately supported substantive domestic and export markets. Mixing of livestock, as well as cultural preferences, led to strategic breeding and genetic gains that have improved livestock phenotypic traits for a range of climates, soils, and flora and fauna to which they were not originally acclimated. Numerous introductions of non-native game species also occurred and altered ecosystem dynamics across the region. Multiple cervid species, the European rabbit, hare, and red fox (*Vulpes vulpes*) were imported to Australia and several of these also soon arrived in New Zealand (Krull et al. 2014). Shipping and human movement also facilitated commensal rodent-island hopping, which has been catastrophic for some bird species across Oceania's islands (Matisoo-Smith and Robins 2008; Towns 2009). Livestock competing for resources, and game species that became invasive in Australia and New Zealand, has impacted the bulk of the continent's landmass and consequently its native wildlife. This was exacerbated by human activity like hunting where the perceived impacts of some species were considered to put sheep husbandry at risk (e.g., the extinction of the Tasmanian tiger (*Thylacinus cynocephalus*; Paddle 2000), while clearing of native vegetation for livestock grazing caused the decimation of numerous other species (Reside et al. 2017).

With European settlers and livestock came diseases that Oceanic humans and native wildlife were ill-prepared for. For native islanders across Oceania, the impacts of diseases such as smallpox were sometimes large. Other introduced diseases that impacted humans during this time period and remain even now include chickenpox, cholera, diphtheria, influenza, measles, scarlet fever, typhoid, typhus, tuberculosis, and pertussis (whooping cough). To a lesser extent, imported livestock diseases impact Oceania's native wildlife. Old World diseases that were introduced to wildlife during this period included leptospirosis, brucellosis, and bovine tuberculosis. Additionally, foot and mouth disease was introduced to Australia during the early 1800s and was eradicated in 1872 (Productivity Commission 2002). The primary diseases found throughout Oceania and the interfaces they occur at can be found in Table 1.

As European populations colonized the larger islands and island chains, livestock trading increased, but innovations in mass land transport of refrigerated goods were not developed yet. Thus, overlanding or droving was common, where livestock grazed hundreds of kilometers to trading posts and urban centers. Gradually, small-scale subsistence farming began to give way to livestock production as a business, primarily in Australia and New Zealand, and to a lesser degree in New Guinea and

Table 1 Major disease systems at the interface of wildlife (W) and livestock (L) in Australia (AUS) and New Zealand (NZ)

Pathogen system	Primary species		Contact	Transmission direction	Distribution	References
	Domestic	Wildlife				
Avian influenza	Poultry	Waterfowl	Direct, indirect	L←W	AUS, NZ	Bulach et al. (2010), Grillo et al. (2015)
Newcastle disease (non-virulent)	Poultry	Migratory birds, native birds	Direct, indirect	L↔W	AUS	Hoque et al. (2012)
Blue tongue	Ruminants	Deer, water buffalo	Direct, indirect	L↔W	AUS	Firth et al. (2017)
Leptospirosis	All	All	Direct, indirect	L↔W	AUS, NZ	Guernier et al. (2018)
Paratuberculosis	Cattle, goats, sheep	Wild ruminants	Direct, indirect	L ← W	AUS, NZ	Abbott (2002), Nugent et al. (2011)
Neospora	Cattle	Wild canids (dog/red fox)	Vector borne	L↔W	AUS	King et al. (2011)
Bovine tuberculosis	Cattle	Australian brushtail possum (wild pig, deer, ferrets, deer)	Direct	L←W	NZ	Nugent et al. (2018)
Swine brucellosis	Swine, dogs	Wild pigs	Direct, indirect	L↔W	AUS	Mason and Fleming 1999
Lyssavirus	All	Wild bats	Indirect	L←W	AUS, NZ	Merritt et al. (2018)
Anthrax	All	All	Direct	L↔W	AUS	Barro et al. (2016)

(continued)

Table 1 (continued)

Pathogen system	Primary species		Contact	Transmission direction	Distribution	References
	Domestic	Wildlife				
Arboviral pathogens: Murray Valley encephalitis, Kunjin, Ross River fever	Vertebrate hosts and the arthropod vectors (e.g., herons and egrets for Murray Valley encephalitis)	All (e.g., marsupials macropods for Ross River fever)	Vector borne	Mackenzie et al. (2017)	AUS	Mackenzie et al. (2017)
Hendra virus	Horses	Flying foxes	Indirect	L←W	AUS	Middleton (2014)

Polynesia. Mechanization advancements fueled this increasing trend, with railroad systems and steam-powered river transports in place by the mid-1800s (DITRDC 2020; Beeson 2020). Technology advanced and the first refrigerated frozen meat was exported from Port Adelaide in South Australia to the United Kingdom in 1895 (Maurovic 2007). Cattle, sheep, and their products could be raised across vast tracks of land, shipped via rail or river systems to human population centers for processing, and then exported globally. These advances led to increased movement of livestock and increased contact among livestock and native animals.

By this time the majority of Australian and New Zealand livestock production had transitioned from open range to behind fences, and though water and feed resources were managed, they were still available to native species as well. Wire-based fencing provided an inexpensive way to enclose large pastures and water sources like artesian bores or windmills that tapped underground water sources and allowed pastoralists to graze cattle and sheep in areas that would otherwise be unproductive for livestock. This led to shared resources that were more concentrated, which resulted in the potential for enhanced wildlife-livestock contact. However, the same production pressures are not evident for the rest of Oceania. This dichotomy is especially evident today where poultry is highly valued for meat in addition to their value from egg production. Poultry across the larger population centers is Oceania's preferred source of protein (Whitnall and Pitts 2019). Oceania's largest land masses and the livestock agriculture they support have changed dramatically in the last 250 years. The region has expended much effort into preventing disease incursions, containing and even eradicating intractable highly contagious animal and human diseases (Sabirovic and O'Neil 1999). Management of diseases considered endemic is undertaken across the largest countries in an effort to maintain their impacts below economic thresholds and to prevent their spread within and among Oceania's islands.

The Prevalent Livestock, Farm Typologies, and Opportunities for Interface

PICTs of Oceania have some of the highest densities of pigs and poultry per arable landmass on earth (Brioudes 2016). Conversely, Australia and New Zealand have large populations of cattle, Asian buffalo, sheep, horses, donkeys, and goats, with the majority of them being free-range or existing within extensive grazing production systems. As a result, these countries have some of the lowest commercial cattle and sheep stocking rates on earth. While a majority of livestock production is extensive, greater intensification is a growing trend and the larger Oceanic islands support intensive and free-range poultry and pig production systems. Cattle and sheep are by far the primary livestock species by population across Oceania by virtue of two countries, Australia and New Zealand.

Australia is one of the largest beef, sheep, and goat meat exporters in the world and is an industry valued at $13.5 billion (Meat and Livestock Australia 2019; Black et al. 2008). Australia is also a large live animal exporter, exporting 1.1 million cattle, and 1.1 million sheep (Meat and Livestock Australia 2019). New Zealand is the top global exporter of milk and butter (FAO 2019). The demand for protein will continue to grow significantly as the world's populations continue to grow. The movement of livestock (dead or alive) may offer rapid spatial and temporal animal disease transmission routes and complicate the management of infectious diseases. Understanding these livestock aggregations and movements, including buying and selling patterns, and rapid identification and tracing of animals from infected premises have been done in Australia to help prevent and manage infectious disease outbreaks in livestock (DAWE 2019).

The Wildlife

Oceania, with its continental islands and more secluded high and low tropical islands, hosts some of the most unique flora and fauna assemblages found anywhere in the world. Plate tectonics and changing sea levels have resulted in ecosystems that have been isolated from the rest of the world for millions of years. It is this remarkable diversity and endemism that has resulted in the region being recognized for encompassing 6 of the world's 39 hotspots of diversity (Mittermeier et al. 2004). Australia is well known for its iconic kangaroos and koalas, as well as hosting the only mammals in the world that lay eggs (e.g., the platypus and four species of echidna). Birds are also relatively common in Oceania, with 110 endemic species occurring there, including many flightless species (e.g., kiwi, emus, cassowaries). The immensely rich coastal communities and oceans surrounding these large and small islands also host many marine species found only in the region.

Most recreational hunting in Australia is of feral or introduced species. Many of these species were introduced by Europeans to create a hunting experience similar to Anglo-Saxon traditions (Sharp and Wollscheid 2009). Hunting primarily occurs on private lands. Highly invasive species, such as rabbits, wild pigs, goats, and certain species of deer, are declared pests by most states and territories and highly encouraged to be hunted. Australia also allows for the commercial harvest of kangaroos and sets annual quotas (Pople 2004). Elsewhere in Oceania, hunting ranges from highly sophisticated operations where hunters pay considerable amounts of money for property access and guiding services (Davys et al. 1999) to local or subsistence hunting which not only provides food and supplies, but also serves religious and cultural functions (Oliver 1989). Waterfowl hunting is also a popular recreational activity in Australia and New Zealand and on other islands in the South Pacific, collection of seabird eggs is important to local indigenous communities (Bauer and Giles 2002).

Although there has been an increasing global trend in research on diseases at the wildlife-livestock interface, publications focusing on the region of Oceania are lacking (Wiethoelter et al. 2015). In New Zealand, tuberculosis (TB) transmission between brushtail possums and livestock, and to a lesser degree wild and farmed deer, has been occurring for decades and is well studied (Morris and Pfeiffer 1995; Warburton and Livingstone 2015; Nugent et al. 2018). As with other countries where TB independently cycles in wildlife reservoirs (i.e., Great Britain, Spain, South Africa, and North America), eliminating TB at the livestock-wildlife interface has been a challenge (Palmer et al. 2012; Gortazar and Cowan 2013). This is partly because humans have over time introduced 31 species of mammals to New Zealand (King 1990), including feral livestock, which now occur naturally in the wild, of which 14 have been documented with TB (Coleman and Cooke 2001).

Also occurring in the region are two emerging bat-borne viruses that occasional spill-over into horses and pigs, Hendra and Nipah viruses, respectively (Mackenzie 2005). Fruit bats are the natural reservoir hosts for both viruses and in Australia, it is suspected that transmission of the Hendra virus is from ingestion of contaminated bat urine or feces on horse feed or water (Prowse et al. 2009). Although Nipah virus outbreaks have only been recognized in Malaysia, India, and Bangladesh, Oceania is nearby with fruit bats as a transmission source having broad spatial overlap throughout the region (Mackenzie and Field 2004; Plowright et al. 2019).

Australia, New Zealand, and other South Pacific islands lie at the southern end of the East-Australasian flyway. For example, 99 bird species are known to move between Australia and Asia and 63 of these undertake frequent migrations (Tracey et al. 2004). It is these wild birds, particularly waterfowl, which use this flyway and have been known to carry and spread high and low pathogenic forms of avian influenza (Viyahkrishna et al. 2013; Endo and Nishiura 2018; Sullivan et al. 2018). Periodically, spill-over events occur, and the virus is transmitted to domestic poultry, swine, or humans. Reducing the spread of avian influenza in migratory birds is unlikely, but increased disease surveillance and heightened biosecurity at the wild bird-poultry interface can lower the risk of disease outbreaks (Glass et al. 2019). Table 1 summarizes the major disease systems at the interface of wildlife and livestock in Australia and New Zealand.

Box 1 Wildlife-Livestock Interfaces in New Caledonia: Artiodactyl Introductions, Invasions and Sympatric Parasite Speciation

The archipelago of New Caledonia is a French Overseas Territory that lies at the southern extremity of Melanesia. The main island of Grand Terre is an ancient land, once part of the great ancient continent of Gondwanaland, from which it became separated 65–80 million years ago (Mittermeier et al. 1996). The flora and fauna are characteristic of an isolated ancient land, with an exceptional diversity and endemism within several plant and invertebrate

(continued)

Box 1 (continued)
groups. With the exception of bats, all terrestrial mammals have been introduced (Pascal et al. 2008). Significant wildlife-livestock interfaces, therefore, only involve species that have been introduced onto the archipelago, either deliberately, such as livestock and game, or not.

Two species of wild ungulates, wild pigs (*Sus scrofa*) and rusa deer (*Rusa timorensis*), are now widespread on the main island of Grande Terre, responsible for extensive negative impacts on native invertebrates, plants, and habitats (de Garine-Wichatitsky et al. 2004). Wild pigs, which are believed to have been first introduced in New Caledonia by the navigator James Cook during the end of the eighteenth century, have extensive impacts on the native flora and fauna, and on crop production (Pascal et al. 2006). However, wild pigs have not been demonstrated to play a role in the maintenance or spread of any diseases of zoonotic or veterinary importance, such as bovine tuberculosis, as in Australia and New Zealand (bovine tuberculosis is currently absent from New Caledonia). Similarly, rusa deer have invaded all natural and human-transformed habitats of Grande Terre, where they have very significant negative impacts on the native vegetation (de Garine-Wichatitsky et al. 2003, 2005), and frequently compete for pastures with free grazing cattle and small ruminants (Fig. 7). The small number of individual deer introduced in 1870 (Barrau and Devambez 1957), as confirmed by genetic analysis (de Garine-Wichatitsky et al. 2009), do not appear to have introduced new pathogens from their native range. Despite repeated screening of wild and farmed populations, rusa deer in New Caledonia appear to harbor few parasites and pathogens, and no significant livestock diseases have been detected in them.

However, the southern cattle tick (*Rhipicephalus microplus, formerly Boophilus microplus*) offers a remarkable example of the far-reaching consequences of wildlife-livestock-parasite interactions. The tick was accidentally introduced to New Caledonia during the mid-twentieth century with the importation of animals from Australia (Chevillon et al. 2013), and quickly invaded the cattle farms of the entire island of Grande Terre, favored by suitable local climatic conditions and the high susceptibility of *B. taurus* cattle breeds that had been imported by Europeans (Barré 2003). Intensive tick control programs have been implemented using acaricides since the tick was introduced onto the island, and resistance to all acaricides used have appeared (Ducornez et al. 2005; Chevillon et al. 2013). Rusa deer were initially considered a poor host for southern cattle tick, because ticks attached to deer are usually unable to engorge fully (Barré et al. 2002). However, significant tick infestation levels on rusa deer have been recorded and a large-scale tick genetic survey has been conducted (Koffi et al. 2006; De Meeûs et al. 2010). The analysis revealed a substantial and highly significant genetic differentiation between sympatric deer ticks and cattle ticks sampled from the same locations (De Meeûs et al. 2010). The southern cattle tick has actually diverged

(continued)

Box 1 (continued)
into two differentiated genetic pools: one on cattle, its original host on which intense acaricide tick control was applied for decades; and one on rusa deer, a new host that is widespread, locally abundant, and not subject to acaricide treatments. Remarkably, this sympatric isolation has occurred over a relative short period of time as a consequence of differential selection pressure, illustrating the complex ecological and evolutionary processes that may occur at wildlife-livestock interfaces.

The Disease at the Interface: One Health Perspective

Wildlife-livestock associated diseases that affect humans and domestic animals present extreme challenges for governmental agencies, natural professionals, and livestock producers. Differing attitudes and perceptions of the problem often reveal controversial opinions on how best to formulate solutions for the management and control of these diseases. A One Health approach to the problem acknowledges that animal and human diseases are intricately related and tools to reduce disease transmission at the animal-human interface must be multi-disciplinary; address the well-being of wildlife, livestock, and humans; incorporate socio-political and

Fig. 7 Introduced cattle and rusa deer frequently interact within pastures in New Caledonia. Photo: Nicolas Barré

economic factors, and account for environmental changes (Keune et al. 2017). For example, some wildlife-livestock diseases put entire industries at risk, such as trade restrictions when TB is found in cattle (Cousins and Roberts 2001; Waters et al. 2012; More et al. 2015). Fortunately, Australia was able to successfully eradicate TB from livestock and wildlife through a whole herd test and slaughter program, abattoir monitoring, extensive tuberculin testing, strict livestock identification via tagging, cost-sharing by government and industry, and removal of feral wildlife known to be reservoirs of TB (Cousins and Roberts 2001; More et al. 2015).

The avian influenza virus is another example of a disease(s) found globally in wild waterfowl, but once transmitted with domestic poultry flocks can cause severe mortality, oftentimes results in culling or depopulating entire premises, trade restrictions, and be a cause for concern for human health (Swayne et al. 2017). Wild bird surveillance has revealed some seasonal trends to increased public health and poultry risk of avian influenza transmission and disease outbreaks (OIE 2018). Climate change and how this might affect movements of migrating waterfowl using the Asian-Australasian flyway is another cause for concern as this may expand the range of current influenza viruses into novel areas (Vijaykrishna et al. 2013). Wild and domestic pigs are also susceptible to various avian and mammalian trains of influenza viruses, some more harmful than others, where genetic reassortment may occur and result in new, highly transmissible strains of the virus (Hall et al. 2008; Wang and Palese 2009).

Recently, a large pig die-off, which was confirmed to be the result of African swine fever, occurred in the Southern Highlands Province of Papua New Guinea (FAO 2020) and has spread to neighboring provinces. African swine fever is a devastating disease affecting both domestic and wild pigs of all ages. Reducing the spread of the disease in Oceania is crucial as pigs not only serve as an important commodity, they are also a vital cultural resource. People that live in the region have been instructed to not move pigs (wild or domestic) or pig meat out of the infected districts and provinces.

The health of humans, wildlife, livestock, and the environment is interconnected and strategies to reduce illness and death in people and animals must be global in approach. Zoonotic diseases from wildlife and associated pathogens spill-over and account for more than half of known human infectious diseases (American Public Health Association 2018). Some wildlife diseases have multiple reservoirs, whether wild or domestic, and pathogen transmission can be bidirectional (Coleman and Cooke 2001; Bengis et al. 2002; Hlokwe et al. 2014). Human population growth and expansion into wildlife habitat is one contributing factor to these disease spill-over events. Climate change and changes in land use is another factor tied to pathogen spread. Increasing globalization or movements of humans, livestock, and sometimes illegal transport of wildlife also leads to the spread of harmful pathogens. We must also acknowledge that infectious diseases should be investigated at local and regional scales as indigenous communities on small, remote islands of Oceania may be more vulnerable to disease outbreaks because existing animal and human populations are immunologically naïve and may be highly susceptible to infectious agents (Horwood et al. 2019).

Box 2 Host Status is not a Species Fixed Characteristic: Tuberculosis and *Sus scrofa* in Oceania (by Joaquín Vicente & Christian Gortázar)

While maintenance hosts can maintain infection in an area in the absence of cross-transmission from other species of domestic or wild animals, spill-over hosts need a continuing acquisition of infection from other species. The transmission of tuberculosis (TB) caused by the *Mycobacterium tuberculosis* complex (MTC) is dependent on a number of factors. The MTC has an extensive host range and the same host species have been introduced in new areas where the disease is present, providing an example to evaluate if host status is a species fixed characteristic. In Oceania and a number of other countries, TB has become established in one or more wildlife hosts capable of independently maintaining the disease. Evidences supporting that wild boar (*Sus scrofa*) in its natural range, Western Europe, is a TB reservoir host include (Naranjo et al. 2008): (1) presence of common MTC genotypes in wild boar, domestic and wild animals and humans, (2) high prevalence of MTC among wild boar in estates fenced for decades in the complete absence of contact with domestic livestock and other wild ungulates, (3) TB lesions are frequently seen in thoracic lymph nodes and lungs, suggesting that respiratory infection and excretion may occur, and (4) extensive tuberculous lesions in more than one anatomical region occur in a high proportion of juvenile wild boar that probably represents the main source of mycobacterial excretion.

Wild pig densities in Oceania may be 10 times lower than wild boar densities in Spain, on average (Acevedo et al. 2006; Hone 1990, see table below). Previous studies found that most wild suids had lesions exclusively in mandibular lymph nodes (e.g., 62% in Australian wild pigs; Corner et al. 1981). In Australia, the low prevalence of generalized TB disease in wild pigs, the absence of pulmonary lesions, the lack of other obvious routes of excretion from infected pigs, and the lack of contact between wild pigs and other species, particularly water buffalo and cattle, lead to the conclusion that wild pigs were spill-over and not a source of TB infection (Corner et al. 1981). TB was essentially eradicated from the bovid population and subsequently almost disappeared from the wild pig population (Corner 2006). To date, only Australia has eradicated TB from a wildlife potential maintenance host (not demonstrated this role) (Fig. 8, Table 2).

In New Zealand, introduced brushtail possums (*Trichosurus vulpecula*) are the most important wild animal maintenance host for TB (Nugent et al. 2015). In contrast, wild deer (predominantly red deer (*Cervus elaphus*)) and wild pigs are considered to be spill-over hosts for MTC, in spite that TB prevalence in New Zealand wild pigs can reach 100%. Elimination of TB from possums (and livestock) resulted in the eventual disappearance of TB from wild pigs and wild deer. The high rate at which pigs acquire MTC infection from dead possums makes them useful as sentinels for detecting TB in wildlife.

(continued)

Box 2 (continued)
Infections in lymph nodes of the head and alimentary tract predominate, indicating that TB is mostly acquired through scavenging TB carrion, particularly possums, infection is usually well contained, and transmission between seems to be rare. The spill-over host status of wild pigs in New Zealand is likely to be the result of comparatively low intra-specific contact rates, which in turn result from the unrestricted year-round New Zealand hunting system reducing average densities to low levels and keeping the pigs widely dispersed. Wild pigs (and wild deer) play a secondary role in the complex epidemiology of TB in New Zealand and their active management is not required for local TB eradication. The national goal is eradicating TB from livestock and wildlife reservoirs by 2055. Unless the disease is often self-sustaining in a variety of wildlife hosts, authorities are well on the way to achieving this outcome based on abundant and rigorous scientific orientated management.

The case of wild pig populations on the Hawaiian island of Molokai is particularly interesting (Essey et al. 1981). After an infected cattle herd was removed from the area, the prevalence of TB in wild pigs declined markedly from 20% to 3.2% (Essey et al. 1983). Initially, it was suggested that the disease was maintained on the island through spill-over from cattle; however, *M. bovis* was detected in wild pigs after the removal of cattle, indicating that the bacteria could persist without cattle.

Management Practices at the Interface

The interface between native wildlife, domestic livestock, and livestock that have gone feral is vastly important from a disease ecology perspective. Infectious diseases can be transmitted from wildlife to livestock and vice versa and information for managing these transmission events is lacking (Rhyan and Spraker 2010). The goal for any management action is to reduce the potential for contact (direct and indirect) and therefore pathogen transmission. Disease outbreaks can threaten the health and well-being of wildlife, livestock, and human populations and can have serious social and economic consequences. Disease detection and surveillance, vaccination, therapy, quarantine, test and slaughter, and depopulation are just a few management practices used to reduce pathogen transmission (Rhyan and Spraker 2010). Infectious contacts between livestock and wildlife will continue to increase as humans encroach into wildlife habitat, remove or alter existing habitat, climate change removes or creates new habitat, and producers intensify livestock production to keep up with human population growth (Gortazar et al. 2007; Black et al. 2008; Decker et al. 2010). Moreover, the recent emergence of novel coronaviruses and the devastating threats they pose to global public health should highly necessitate future

Fig. 8 Wild pig-livestock interfaces in Oceania. (**a–b**) Wild pigs grazing in proximity to horses in Hawaii (images: USDA). (**c–f**) Wild pig-cattle interface in Australian savanna (images **c–f**: Brendan Cowled and Steve Lapidge). (**c**) and (**d**) illustrate wild pigs roaming and grazing near rangeland cattle, (**e**) shows potential indirect interaction at water sites, and (**d**) represents a wild pig scavenging on a cattle carcass. For comparison, see Figs. 2 and 3 of Chapter "Characteristics and Perspectives of Disease at the Wildlife-Livestock Interface in Europe" for wild boar in Europe

research into emerging wildlife and zoonotic diseases (Ahmad et al. *In Press*; Bonilla-Aldana et al. 2020).

Controlling diseases at the wildlife-livestock interface is tremendously complex, with state and federal agencies, wildlife managers, and livestock producers having to address environmental, biological, and social issues. Oceania, with some of its outlying regions or islands, has the luxury of not having to deal with some global diseases transmitted at this interface due to its remoteness or isolation. New Zealand represents a unique regional marsupial-cattle interface where brushtail possums are

Table 2 Comparative data on wild pig and wild boar ecology and TB epidemiology

	Australia	New Zealand	Molokai (Hawaii)	South and central Spain	References
Animals/km^2	<11	1 pig/km^2 (entire area occupied)	>8km^2	Up to 90 pig/km^2	Corner et al. (1981), Acevedo et al. (2007), Mayer and Brisbin (2008)
TB prevalence	0–40%	Up to 100%	0,2	18–100%	Corner et al. (1981), Wakelin and Churchman (1991), Knowles (1994), Lugton (1997), Vicente et al. (2006, 2007)
Prevalence trend	Decreasing	Decreasing	¿?	Increasing	Vicente et al. (2013), Corner (2006), Essey et al. (1983)
Lung lesions	Not found	0–63%	77% (7/9 culture + individuals	38–52%	Corner et al. (1981), Gortazar et al. (2003), Martín-Hernando et al. (2007)
Percent generalized	25%	0–63%	Unreported	58%	Lugton (1997), Nugent et al. (2002)
TB host status	Spill-over	Spill-over	Reservoir	Reservoir	Corner (2006), Vicente et al. (2006, 2007)
Other relevant hosts	Buffalo	Possum, red deer, ferret, cattle	Cattle	Red deer, fallow deer, livestock	McInerney et al. (1995), Essey et al. (1981), Gortazar et al. (2011), Nugent et al. (2001)

the maintenance reservoir host for *M. bovis*. The preferred method to stop or reduce transmission of bTB to cattle herds is lethal control or culling of possums (Caley et al. 1999; Nugent et al. 2011; Green and Rohan 2012). Australia eliminated bTB from domestic cattle in 2006, representing a major Commonwealth, State, and Territory governmental success story and providing considerable benefits to the cattle industry. To help achieve this goal, national eradication programs were implemented, which included: improved livestock identification, a cattle test and slaughter program, improved diagnostic tests, national herd traceback programs, severe restrictions on cattle movement, and being fortunate that there was no feral wildlife that were reservoirs of *M. bovis* (Cousins and Roberts 2001; Turner 2011; Gormley and Corner 2018). Feral water buffalo (*Bubalus bulalis)* were the exception, but they were eradicated in areas where there was evidence of bTB in the wild population (Radunz 2006). The eradication campaign also included financial assistance and subsidies to help offset the costs of mustering and holding cattle to be tested, low-interest loans for temporary cattle yards, constructing water facilities, fencing, and restocking freight fees (Radunz 2006).

Transmission of pathogenic avian influenza occasionally occurs in poultry in Australia. Control currently includes culling poultry, whether commercial facilities or "backyard" operations and improved biosecurity where measures are lacking (Tracey et al. 2004). Improved biosecurity measures at poultry facilities include restrictions on water access and treatment, secure feed storage areas, and improved cleaning of sheds (East 2007; DAWE 2009; Glass et al. 2019).

Hendra virus is believed to be transmitted from fruit bat to horse, horse to dog, and horse to human (Queensland Governement 2018). Monitoring the distribution and abundance of fruit bats, the primary host of the Hendra virus, in Australia is essential to predicting disease risk to livestock and humans. Spill-over risk may be lowered via roost dispersal or modification activities, but best management techniques need to be developed (Edson et al. 2015). A registered vaccine to help prevent Hendra virus disease in horses is available and is the most effective way to manage the disease. Other methods believed to reduce virus transmission at the wildlife-livestock interface include: removing horse feed and water from under trees and possible place under shelters, removing horses from paddocks that are routinely visited by fruit bats (e.g., bats visiting flowering/fruiting trees), fencing off areas in paddocks that contain flowering/fruiting trees, removing horses from paddocks during peak fruit bat activity periods (i.e., dusk through the night).

References

Abbott KA (2002) Prevalence of Johne's disease in rabbits and kangaroos. Technical report, University of Sydney December 2000. Meat and Livestock Australia limited, Australia

Acevedo P, Escudero MA, Muñoz R, Gortazar C (2006) Factors affecting wild boar abundance across an environmental gradient in Spain. Acta Theriol 51:327–336

Acevedo P, Vincente J, Höfle U, Cassinello J, Ruiz-Fons F, Gortazar C (2007) Estimation of European wild boar relative abundance and aggregation: a novel method in epidemiological risk assessment. Epidemiol Infect 135:519–527

Ahmad T, Khan M, Haroon, Musa TH, Nasir S, Hui J, Bonilla-Aldana DK, Rodriguez-Morals R (in press) Covid-19: zoonotic aspects. Travel Med Infect Dis

Alexandratos N, Bruinsma J (2012) World agriculture towards 2030/2050: the 2012 revision. ESA working paper no. 12-03, FAO, Rome

American Public Health Association (2018) Advancing a 'one health' approach to promote health at the human-animal-environment interface. Policy statement 201712

Anderson A (2009) The rat and the octopus: initial human colonization and the prehistoric introduction of domestic animals to remote Oceania. Biol Invasions 11:1503–1519

Australian Bureau of Statistics (2001) Yearbook Australia. Number 83, ABS Catalogue No. 1301.0. Canberra, AU

Barrau J, Devambez L (1957) Quelques résultats inattendus de l'acclimatation en Nouvelle-Calédonie. Terre et Vie 4:324–334

Barré N (2003) *Boophilus microplus* resistance to deltamethrin in New Caledonia. International seminar in animal parasitology. World situation of parasite resistance in veterinary medicine. SENASICA-INIFAP-INFARVET-UADY-FAO-AMPAVE, Merida, Yucatan, Mexico, pp 11–16

Barré N, Bianchi M, de Garine-Wichatitsky M (2002) Effect of the association of cattle and rusa deer *(Cervus timorensis russa)* on populations of cattle ticks *(Boophilus microplus)*. Ann N Y Acad Sci 969:280–289

Barro AS, Fegan M, Moloney B, Porter K, Muller J, Warner S, Blackburn JK (2016) Redefining the Australian Anthrax Belt: modeling the ecological niche and predicting the geographic distribution of *Bacillus anthracis*. PLoS Negl Trop Dis 10(6):e0004689

Bauer J, Giles J (2002) Recreational hunting – an international perspective. Wildlife Tourism Research Report Series: No. 13

Beeson G (2020) A water story: learning from the past, planning for the future. CSIRO Publishing Clayton South VIC, AU

Bengis RG, Kock RA, Fischer J (2002) Infectious animal diseases: the wildlife/livestock interface. Rev Sci Tec Off Int Epiz 21(1):53–65

Black PF, Murray JG, Nunn MJ (2008) Managing animal disease risk in Australia: the impact of climate change. Rev Sci Tec Off Int Epiz 27(2):563–580

Bonilla-Aldana DK, Dhama K, Rodriguez-Morals AJ (2020) Revisiting the one health approach in the context of COVID-19: a look into the ecology of this emerging disease. Adv Anim Vet Sci 8 (3):234–237

Bourke RM, Harwood T (eds) (2009) Food and agriculture in Papau New Guinea. Australian National University E Press, Canberra, AU

Bradshaw CJA (2012) Little left to lose: deforestation and forest degradation in Australia since European colonization. J Plant Ecol 5(1):109–120

Brioudes A (2016) Livestock disease surveillance and biosecurity priorities in the Pacific Island countries and territories. Dissertation, James Cook University, Queensland, AU

Bulach D, Halpin R, Spiro D, Pomeroy L, Janies D, Boyle DB (2010) Molecular analysis of H7 avian influenza viruses from Australia and New Zealand: genetic diversity and relationships from 1976 to 2007. J Virol 84:9957–9966

Caley P, Hickling GJ, Cowan PE, Pfeiffer DU (1999) Effects of sustained control of brushtail possums on levels of *Mycobacterium bovis* infection in cattle and brushtail possum populations from Hokotaka, New Zealand. N Z Vet J 47(4):133–142

Chapman AD (2009) Numbers of living species in Australia and the world, 2nd edn. Australian Government, Department of the Environment, Water, Heritage, and the Arts, Canberra, AU

Chevillon C, de Garine-Wichatitsky M, Barré N, Ducornez S, De Meeus T (2013) Understanding the genetic, demographical and/or ecological processes at play in invasions: lessons from the southern cattle tick *Rhipicephalus microplus* (Acari: Ixodidae). Exp Appl Acarol 59:203–218

Coleman JD, Cooke MM (2001) Mycobacterium bovis infection in wildlife in New Zealand. Tuberculosis 81(3):191–202

Cook BD, Fenner F (2002) Rabbit haemorrhagic disease and the biological control of wild rabbits, Oryctrolagus cuniculus, in Australia and New Zealand

Corner LA (2006) The role of wild animal populations in the epidemiology of tuberculosis in domestic animals: how to assess the risk. Vet Microbiol 112:303–312

Corner LA, Barrett RH, Lepper AWD, Lewis V, Pearson CW (1981) A survey of mycobacteriosis of feral pigs in the northern territory Aust. Vet J 57:537–542

Cousins DV, Roberts JL (2001) Australia's campaign to eradicate bovine tuberculosis: the battle for freedom and beyond. Tuberculosis 81(1/2):5–15

Crump JA, Murdoch DR, Baker MG (2001) Emerging infectious diseases in an island ecosystem: the New Zealand perspective. Emerg Infect Dis 7(5):767–772

Davys TR, Forsyth DM, Hickling GJ (1999) Recreational Himalayan thar (*Hemitragus jemlahicus*) hunters in Canterbury, New Zealand: a profile and management implications. N Z J Zool 26:1–9

de Garine-Wichatitsky M, Duncan P, Labbé A, Suprin B, Chardonnet P, Maillard D (2003) A review of the diet of rusa deer *Cervus timorensis russa* in New Caledonia: are the endemic plants defenceless against this introduced, eruptive ruminant? Pac Conserv Biol 9:136–143

de Garine-Wichatitsky M, Chardonnet P, de Garine I (2004) Management of introduced game species in New Caledonia : reconciling biodiversity conservation and resource use? Game Wildlife Sci 21:697–706 de Garine-Wichatitsky M, Soubeyran Y, Maillard D, Duncan P (2005) The diets of introduced rusa deer (*Cervus timorensis russa*) in a native sclerophyll forest and a native rainforest of New Caledonia. N Z J Zool 32:117–126

de Garine-Wichatitsky M, de Meeûs T, Chevillon C, Berthier D, Barré N, Thévenon S, Maillard JC (2009) Population structure of wild and farmed rusa deer *(Cervus timorensis russa)* in new-Caledonia inferred from polymorphic microsatellite loci. Genetica 137:313–323

De Meeûs T, Koffi BB, Barré N, de Garine-Wichatitsky M, Chevillon C (2010) Swift sympatric adaptation of a species of cattle tick to a new deer host in New Caledonia. Infect Genet Evol 10:976–983

Decker DJ, Evensen DN, Siemer WF, Leong KM, Riley SJ, Wild MA, Castle KT, Higgins CL (2010) Understanding risk perceptions to enhance communications about human-wildlife interactions and the impacts of zoonotic disease. ILAR J 51(3):255–261

Departement of Infrastructure, Transport, Regional Development and Communications (DITRDC) (2020) History of rail in Australia. Australian Government, Canberra, AU

Department of Agriculture, Water and the Environment (DAWE) (2009) National farm biosecurity manual – poultry production. Australian Government, Canberra, AU

Department of Agriculture, Water and the Environment (DAWE) (2019) Livestock movement summary. Australian Government, Canberra, AU

Ducornez S, Barre N, Miller RJ, Garine-Wichatitsky M (2005) Diagnosis of amitraz resistance in *Boophilus microplus* in New Caledonia with the modified larval packet test. Vet Parasitol 130:285–292

East IJ (2007) Adoption of biosecurity practices in the Australian poultry industries. Aust Vet J 85 (3):107–112

Eather J (2020) Beef and veal: march quarter (2020) Australian government, Department of Agriculture, Water and the Environment

Edson D, Field H, McMichael L, Jordan D, Kung N, Mayer D, Smith C (2015) Flying-fox roost disturbance and Hendra virus spill-over risk. PLoS One 10(5):e0125881

Edwards GP, Dobbie W, Berman DM (2002) Population trends in European rabbits and other wildlife of Central Australia in the wake of rabbit haemorrhagic disease. Wildl Res 29:557–565

Endo A, Nishiura H (2018) The role of migration in maintaining the transmission of avian influenza in waterfowl: a multisite multispecies transmission model along east Asian-Australian flyway. Can J Infect Dis Med Microbiol 3420535:1–7

Essey MA, Payne RL, Himes EM, Luchsinger D (1981) Bovine tuberculosis surveys of axis deer and feral swine on the Hawaiian island of Molokai. Proc U S Anim Health Assoc 85:538–549

Essey MA, Stallknecht DE, Himes EM, Harris SK (1983) Follow-up survey of feral swine for Mycobacterium bovis infection on the Hawaiian island of Molokai. Proc Annu Meet US Anim Health Assoc 87:589–595

Field H, de Jong C, Melvill D, Smith C, Smith I, Broos A, Kung YH, McLaughlin A, Zeddeman A (2011) Hendra virus infection dynamics in Australian fruit bats. PLoS One 6(12):e28678

Firth C, Blasdell KR, Amos-Ritchie R, Sendow I, Agnihotri K, Boyle DB, Daniels P, Kirkland PD, Walker PJ (2017) Genomic analysis of bluetongue virus episystems in Australia and Indonesia. Vet Res 48:82

Flexner JL (2014) Historical archaeology, contact, and colonialism in Oceania. J Archaeol Res 22:43–87

Food and Agriculture Organization of the United Nations (FAO) (2019) Dairy market review. FAO, Rome

Food and Agriculture Organization of the United Nations (FAO) (2020) ASF situation in Asia update. FAO, Rome

Glass K, Barnes B, Scott A, Toribio JA, Moloney B, Singh M, Hernandez-Jover M (2019) Modelling the impact of biosecurity practices on the risk of high pathogenic avian influenza outbreaks in Australian commercial chicken farm. Prev Vet Med 165(1):8–14

Gormley E, Corner LAL (2018) Wild animal tuberculosis: stakeholder value systems and management of disease. Front Vet Sci 5:327

Gortazar C, Cowan P (2013) Introduction to this issue: dealing with TB in wildlife. Epidemiol Infect 141(7):1339–1341

Gortazar C, Vicente J, Gavier-Widen D (2003) Pathology of bovine tuberculosis in the European wild boar (*Sus scrofa*). Vet Rec 152:779–780

Gortazar C, Ferroglio E, Hofle U, Frolich K, Vicente J (2007) Diseases shared between wildlife and livestock: a European perspective. Eur J Wildl Res 53(4):241–256

Gortazar C, Vicente J, Boadella M, Balesteros C, Galinto RC, Garrido J, Aranaz A, De la Fuente J (2011) Progress in the control of bovine tuberculosis in Spanish wildlife. Vet Microbiol 151:170–178

Green W, Rohan M (2012) Opposition to aerial 1080 poisoning for control of invasive mammals in New Zealand risk perceptions and agency responses. J R Soc N Z 42(3):185–213

Grillo VL, Arzey KE, Hansbro PM, Hurt AC, Warner S, Bergfeld J, Burgess GW, Cookson B, Dickason CJ, Ferenczi M, Hollingsworth T, Hoque M, Jackson RB, Klaassen M, Kirkland PD, Kung NY, Lisovski S, O'Dea MA, O'Riley K, Roshier D, Skerratt LF, Tracey JP, Wang X, Woods R, Post L (2015) Avian influenza in Australia: a summary of 5 years of wild bird surveillance. Aust Vet J 93:387–393

Guernier V, Goarant C, Benschop J, Lau CL (2018) A systematic review of human and animal leptospirosis in the Pacific Islands reveals pathogen and reservoir diversity. PLoS Negl Trop Dis 12(5):e0006203

Hall JS, Minnis RB, Campbell TA, Barras S, DeYoung RW, Pabilonia K, Avery ML, Sullivan H, Clark L, McLean RG (2008) Influenza exposure in United States feral swine populations. J Wildl Dis 44(2):263–368

Hlokwe TM, van Helden P, Michel AL (2014) Evidence of increasing intra and inter-species transmission of Mycobacterium bovis in South Africa: are we losing the battle. Prev Vet Med 115:10–17

Hone J (1990) Predator prey theory and feral pig control, with emphasis on evaluation of shooting from a helicopter Aust. Wildl Res 17:123–130

Hone J, Donnelly CA (2008) Evaluating evidence of association of bovine tuberculosis in cattle and badgers. J Appl Ecol 45:1600–1666

Hoque MA, Burgess GW, Karo-Karo D, Cheam AL, Skerratt LF (2012) Monitoring of wild birds for Newcastle disease virus in North Queensland, Australia. Prev Vet Med 103:49–62

Horwood PF, Tarantola A, Goarant C, Matsui M, Klement E, Umezaki M, Navarro S, Greenhill AR (2019) Health challenges of the Pacific Region: insights from history, geography, social determinants, genetics, and the microbiome. Front Immunol 10:2184

Jupiter S, Mangubhai S, Kingsford RT (2014) Conservation of biodiversity in the Pacific Islands of Oceania: challenges and opportunities. Pac Conserv Biol 20(2):206–220

Kepple G, Morrison C, Meyer J-Y, Boehmer HJ (2014) Isolated and vulnerable: the history and future of Pacific Island terrestrial biodiversity. Pac Conserv Biol 20(2):136–145

Keune H, Flandroy L, Thys S, De Regge N, Mori M, Antoine-Moussiaux N, Vanhove MP, Rebolledo J, Van Gucht S, Deloauwe I, Hiemstra W, Hasler B, Binot A, Savic S, Ruegg SR, Vries SD, Garnier J, van de Berg T (2017) The need for European OneHealth/EcoHealth networks. Arch Public Health 75:64

King CM (1990) The handbook of New Zealand mammals. Oxford University Press, Auckland

King JS, Jenkins D, Ellis J, Fleming PJS, Windsor PA, Jan S (2011) Implications of wild dog ecology on the sylvatic and domestic life cycle of *Neospora caninum* in Australia. Vet J 188:24–33

Kiple KF (2007) A moveable feast: ten millennia of food globalization. Cambridge University Press, Cambridge, UK

Knight C (2009) The paradox of discourse concerning deforestation in New Zealand: a historical survey. Environ History 15(3):323–342

Knowles GJE (1994) Use of the Judas pig methodology for controlling tuberculosis in feral pigs. MAF quality management contract report 73/90, prepared for the animal health board

Koffi BB, De Meeus T, Barré N, Durand P, Arnathau C, Chevillon C (2006) Founder effects, inbreeding and effective sizes in the southern cattle tick: the effect of transmission dynamics and implications for pest management. Mol Ecol 15:4603–4611

Krull CR, Galbraith JA, Glen AS, Nathan HW (2014) Invasive vertebrates in Australia and New Zealand. In: Stow A, Maclean N, Holwell GI (eds) Austral ark: the state of wildlife in Australia and New Zealand. Cambridge University Press, Cambridge and London, UK, pp 197–226

Lugton LW (1997) The contribution of wild mammals to the epidemiology of tuberculosis (*Mycobacterium bovis*) in New Zealand. PhD dissertation, Massey University, Palmerstown North, New Zealand. http://epicentre.massey.ac.nz/Portals/0/EpiCentre/Downloads/Publications/Thesis/IanLugt onPhD.pdf

Mackenzie JS (2005) Emerging zoonotic encephalitis viruses: lessons from Southeast Asia and Oceania. J Neurovirol 11(5):434–440

Mackenzie JF, Field HE (2004) Emerging encephalitogenic viruses: lyssaviruses and henipaviruses transmitted by frugiverous bats. Arch Virol Suppl 2004(18):97–111

Mackenzie JS, Lindsay MDA, Smith DW, Imrie A (2017) The ecology and epidemiology of Ross River and Murray Valley encephalitis viruses in Western Australia: examples of one health in action. Trans R Soc Trop Med Hyg 111:248–254

Martín-Hernando M, Hofle U, Vicente J, Ruiz-Fons F, Vidal D, Barral M, Garrido JM, de la Fuente J, Gortazar C (2007) Lesions associated with *Mycobacterium tuberculosis* complex infection in the European wild boar. Tuberculosis 87:360–367

Mason RJ, Fleming PJ (1999) Serological survey for Brucella antibodies in feral pigs from eastern Australia. Aust Vet J 77:331–332

Matisoo-Smith E, Robins J (2008) Mitochondrial DNA evidence for the spread of rats through Oceania. Biol Invasions 11(7):1521–1527

Maurovic R (2007) Port Adelaide works to MEAB. In: The meat game: a history of the Gepps cross abiattors and livestock markets. Wakefield Press, Kent Town, pp 53–62

Mayer JJ, Brisbin L (2008) Wild pigs in the United States: their history, comparative morphology, and current status. University of Georgia Press, Athens

McInerney J, Small K, Caley P (1995) Prevalence of Mycobacterium bovis infection in feral pigs in the Northern Territory. Aust Vet J 72:448–451

McNeely JA, Miller KR, Reid WV, Mittermeier RA, Werner TB (1990). Conserving the world's biological diversity. IUCN, Gland, Switzerland; WRI, CI, WWF-US, World Bank, Washington, DC

Meat and Livestock Australia (2019) 2019 state of the industry report – the Australian red meat and livestock industry. North Sydney, AU

Merritt T, Taylor K, Cox-Witton K, Field H, Wingett K, Mendez D, Power M, Durrheim D (2018) Australian bat lyssavirus. Aust J Gen Pract 47:93–96

Middleton D (2014) Hendra virus. Vet Clin North Am Equine Pract 30:579–589

Mittermeier RA, Werner TB, Lees A (1996) New Caledonia – a conservation imperative for an ancient land. Oryx 30:104–112

Mittermeier RA, Gil PR, Hoffmann M, Pilgrim J, Brooks T, Mittermeier CG, Lamoreux J, Da Fonseca GB (2004) Hotspots revisited: Earth's biologically richest and most endangered terrestrial ecoregions. Cemex, Mexico City, Mexico

More SJ, Radunz B, Glanville RJ (2015) Lessons learned during the successful eradication of bovine tuberculosis from Australia. Vet Rec 177(9):224–232

Morris RS, Pfeiffer DU (1995) Directions and issues in bovine tuberculosis epidemiology and control in New Zealand. N Z Vet J 43(7):256–265

Naranjo V, Gortazar C, Vicente J, de la Fuente J (2008) Evidence of the role of European wild boar as a reservoir of *Mycobacterium tuberculosis* complex. Vet Microbiol 127:1–9

Nugent G, Fraser KW, Asher GW, Tustin KG (2001) Advances in New Zealand mammalogy 1990–2000: Deer. J R Soc N Z 31:263–298

Nugent G, Whitford J, Young N (2002) Use of released pigs as sentinels for Mycobacterium bovis. J Wildl Dis 38:665–677
Nugent G, Warburton B, Thomson C, Sweetapple P, Ruscoe WA (2011) Effect of prefeeding, sowing rate and sowing pattern on efficacy of aerial 1080 poisoning of small-mammal pests in New Zealand. Wildl Res 38(3):249–259
Nugent G, Gortazar C, Knowles G (2015) The epidemiology of Mycobacterium bovis in wild deer and feral pigs and their roles in the establishment and spread of bovine tuberculosis in New Zealand wildlife. N Z Vet J 25:54–67
Nugent G, Gormley AM, Anderson DP, Crews K (2018) Roll-Back eradication of bovine tuberculosis (TB) from wildlife in New Zealand: concepts, evolving approaches, and Progress. Front Vet Sci 5:277
O'Neil BD, Pharo HJ (1995) The control of bovine tuberculosis in New Zealand. N Z Vet J 43:249–255
OIE (2018) OIE situational report for avian influenza. World Organisation for Animal Health, 12
Oliver D (1989) Oceania: the native cultures of Australia and the Pacific islands. University of Hawaii Press, Honolulu, Hawaii
Paddle R (2000) The last Tasmanian tiger: the history and extinction of the Thylacine. Cambridge University Press, Cambridge, UK
Palmer MV, Thacker TC, Waters WR, Gortazar C, Corner LL (2012) *Mycobacterium bovis:* a model pathogen at the interface of livestock, wildlife, and humans. Vet Med Int 2012:236205
Pascal M, Barré N, de Garine-Wichatitsky M, Lorvelec O, Frétey T, Brescia F, Jourdan H (2006) Les peuplements néo-calédoniens de vertébrés: invasions, disparitions. In: Beauvais M-L, Coléno A, Jourdan H (eds) Les espèces envahissantes dans l'archipel néo-calédonien. IRD Editions, Paris, pp 111–162
Pascal M, Lorvelec O, Barré N, de Garine-Wichatitsky M (2008) Espèces allochtones d'Esperitu Santo. Premiers résultats de l'expédition Santo 2006. Journal de la Société des Océanistes 126–127:187–193
Plowright RK, Becker DJ, Crowley DE, Washburne AD, Huang T, Nameer PO, Gurley ES, Han BA (2019) Prioritizing surveillance of Nipah virus in India. PLoS One 13(6):e0007393
Pople AR (2004) Population monitoring for kangaroo management. Aust Mammal 26:37–44
Productivity Commission (2002) Impact of a foot and mouth disease outbreak on Australia. Research Repot, Commonwealth of Australia, Canberra, AU
Prowse SJ, Perkins N, Field H (2009) Strategies for enhancing Australia's capacity to respond to emerging infectious diseases. Vet Ital 45(1):67–78
Queensland Government (2018) Reducing the risk of Hendra virus infection. Brisbane, AU
Radunz B (2006) Surveillance and risk management during the latter stages of eradication: experiences from Australia. Vet Microbiol 112(2006):283–290
Reside AE, Beher J, Cosgrove AJ, Evans MC, Seabrook L, Silcock JL, Wenger AS, Maron M (2017) Ecological consequences of land clearing and policy reform in Queensland. Pac Conserv Biol 23(3):219–230
Ridoutt C, Lee A, Moloney B, Massey PD, Charman N, Jordan D (2014) Detection of brucellosis and leptospirosis in feral pigs in New South Wales. Aust Vet J 92(9):343–347
Rhyan J, Spraker T (2010) Emergence of diseases from wildlife reservoirs. Vet Pathol 47(1):34–39
Sabirovic M, O'Neil BD (1999) Managing animal health emergencies through prevention and preparedness in Oceania. Reveu Scientifique Et Technique-Office International Des Epizooties 18(1):38–46
Sharp R, Wollscheid K (2009) An overview of recreational hunting in North America, Europe and Australia. In: Dickson B, Hutton J, Adams WM (eds) Recreational hunting, conservation and rural livelihoods: science and practice. Blackwell Publishing Ltd, Oxford, UK, pp 25–38
Shi H, Singh A, Kant S, Zhu Z, Waller E (2005) Integrating habitat status, human population pressure, and protection status into biodiversity conservation priority setting. Conserv Biol 19 (4):1273–1285

Stewart R (2006) An economic survey of developing countries in the Pacific region. Australian Government, Treasury Department Canberra, pp 91–115

Storey AA, Athens JS, Bryant D, Carson M, Emery K, deFrance S, Higham C, Huynen L, Intoh M, Jones S, Kirch PV, Ladefoged T, McCoy P, Morales-Muniz A, Quiroz D, Reitz E, Robins J, Walter R, Matisoo-Smith E (2012) Investigating the global dispersal of chickens in prehistory using ancient mitochondrial DNA signatures. PLoS One 7(7):e39171

Sullivan JD, Takekawa JY, Spragens KA, Newman SH, Xiao X, Leader PJ, Smith B, Prosser DJ (2018) Waterfowl spring migratory behavior and avian influenza transmission risk in the changing landscape of the east Asian-Australian flyway. Front Ecol Evol 6:206

Swayne DE, Hill RE, Clifford J (2017) Safe application of regionalization for trade in poultry and poultry products during highly pathogenic avian influenza outbreaks in the USA. Avian Pathol 46(2):125–130

Towns DR (2009) Eradications as reverse invasions: lessons from Pacific rat (*Rattus exulans*) removals on New Zealand islands. Biol Invasions 11:1719–1733

Tracey JP, Woods R, Rosheir D, West P, Saunders GR (2004) The role of wild birds in the transmission of avian influenza for Australia: an ecological perspective. Emu 104:109–124

Turner AJ (2011) Endemic disease control and regulation in Australia 1901-2010. Aust Vet J 89 (10):413–421

United Nations (2019) World urbanization prospects: the 2018 revision. Department of Economic and Social Affairs, Population Division, New York

Vicente J, Höfle U, Garrido JM, Fernández-de-Mera IG, Juste R, Barral M, Gortazar C (2006) Wild boar and red deer display high prevalence of tuberculosis-like lesions in Spain. Vet Res 37:107–119

Vicente J, Hofle U, Garrido JM, Fernández-de-Mera IG, Acevedo P, Juste R, Barral M, Gortazar C (2007) Risk factors associated with the prevalence of tuberculosis-like lesions in fenced wild boar and red deer in south-Central Spain. Vet Res 38:451–464

Vicente J, Barasona JA, Acevedo P, Ruíz-Fons JF, Boadella M, Díez-Delgado I, Beltrán-Beck B, González-Barrio D, Queirós J, Montoro V, Fuente JD, Gortázar C (2013) Temporal trend of tuberculosis in wild ungulates from Mediterranean Spain. Transbound Emerg Dis 60(Suppl 1):92–103

Victoriano AFB, Smythe LD, Gloriani-Barzaga N, Cavinta LL, Kasai T, Limpakarnjanarat K, Ong BL, Yanagihara Y, Yoshida SI, Adler B (2009) Leptospirosis in the Asia Pacific region. BioMed Central Infect Dis 9:147

Vijaykrishna D, Deng Y, Su YF, Fourment M, Iannello P, Arzey GG, Hansbro PM, Arzey KE, Kirkland PD, Warner S, O'Riley K, Barr IG, Smith GD, Hurt AC (2013) The recent establishment of north American H10 lineage influenza viruses in Australian Wild waterfowl and the evolution of Australian avian influenza viruses. J Virol 87(18):10182–10189

Wakelin CA, Churchman OT (1991) Prevalence of bovine tuberculosis in feral pigs in Central Otago. Surveillance 18:19–20

Wang TT, Palese P (2009) Unraveling the mystry of swine influenza virus. Cell 137(6):983–985

Warburton B, Livingstone P (2015) Managing and eradicating wildlife tuberculosis in New Zealand. N Z Vet J 63(1):77–88

Waters WR, Palmer MV, Buddle BM (2012) Vordermeier HM (2012) bovine tuberculosis vaccine research: historical perspectives and recent advances. Vaccine 30:2611–2622

Whitnall T, Pitts N (2019) Meat consumption: analysis of global meat consumption trends. Australian government, department of agriculture, Water and the Environment, Canberra

Wiethoelter AK, Betran-Alcrudo D, Kock R, Mor SM (2015) Global trends in infectious diseases at the wildlife-livestock interface. Proc Natl Acad Sci 112(31):9662–9667