Open data and interoperability standards: opportunities for animal welfare in extensive livestock systems

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Abstract

Extensive livestock farming constitutes a sizeable portion of agriculture, not only in relation to land use, but in contribution to feeding a growing human population. In addition to meat, it contributes other economically valuable commodities such as wool, hides and other products. The livestock industries are adopting technologies under the banner of Precision Livestock Farming (PLF) to help meet higher production and efficiency targets as well as help to manage the multiple challenges impacting the industries, such as climate change, environmental concerns, globalisation of markets, increasing rules of governance and societal scrutiny especially in relation to animal welfare. PLF is particularly dependent on the acquisition and management of data and metadata and on the interoperability standards that allow data discovery and federation. A review of interoperability standards and PLF adoption in extensive livestock farming systems identified a lack of domain specific standards and raised questions related to the amount and quality of public data which has potential to inform livestock farming. A systematic review of public datasets, which included an assessment based on the principles that data must be findable, accessible, interoperable and reusable (FAIR) was developed. Custom software scripts were used to conduct a dataset search to determine the quantity and quality of domain specific datasets yielded 419 unique Australian datasets directly related to extensive livestock farming. A FAIR assessment of these datasets using a set of non-domain specific, general metrics showed a moderate level of compliance. The results suggest that domain specific FAIR metrics may need to be developed to provide a more accurate data quality assessment, but also that the level of interoperability and reusability is not particularly high which has implications if public data is to be included in decision support tools. To test the usefulness of available public datasets in informing decision support in relation to livestock welfare, a case study was designed and farm animal welfare elements were extracted from Australian welfare standards to guide a dataset search. It was found that with few exceptions, these elements could be supported with public data, although there were gaps in temporal and spatial coverage. The development of a geospatial animal welfare portal including these datasets further explored and confirmed the potential for using public data to enhance livestock welfare.

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Statement of authorship and originality

This thesis contains no materials published elsewhere nor extractions from a thesis by which I have qualified for or been awarded another degree or diploma, except where explicitly stated. Where another person's work has been used or relied on in this thesis, due acknowledgment was given within the main text and the listing of references.

The following papers have been included as part of this thesis, and the co-author contributions are acknowledged.

Title	**Christiane Bahlo**	**Peter Dahlhaus**	**Helen Thompson**
The role of interoperable data standards in precision livestock farming in extensive livestock systems: a review	85%	10%	5%
Livestock data – is it FAIR yet? A systematic review of livestock farming datasets in Australia	85%	15%	-
Can we improve livestock welfare with public data? An Australian case study	85%	15%	-

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Agricultural Information Management Standards Portal (AIMS): An initiative of the Food and Agriculture Organization of the United Nations (FAO), AIMS is a collection of agricultural standards, technology and best practices related to open data (FAO 2021b).

Agricultural Metadata Element set (AgMES): A set of semantic standards for agriculture, developed by the FAO (FAO 2021a).

Agrovoc: A linked open dataset, thesaurus and vocabulary for agriculture (Caracciolo et al., 2013), published by the FAO.

AgroXML: A Data exchange standard, developed in Germany that is no longer maintained and now replaced by AgroRDF (Goense, 2017).

AgXML: A standardised data format for the agricultural domain (Nikkilä et al., 2012).

Application Programming Interface (API): An interface between software applications with a defined set of requests and parameters.

Data federation: The combined use of disparate datasets from a variety of sources.

Dublin Core Metadata Initiative (DCMI): An organisation that facilitates metadata design, development and best practices (DCMI 2021)

Extensible Markup Language (XML): A markup language and data interchange format for data and documents that is both human and machine readable.

JavaScript Object Notation (JSON): A dataset interchange format based on the JavaScript programming language that is readable by humans and machines.

Open data: Data that is findable and freely available for everyone to use.

Open Source Software (OSS): Software available under permissive licences that allow the use, re-use and modification of source code. Also referred to as free and open software (FOSS), to indicate it is free to use.

Precision Livestock Farming (PLF): The use of advanced technologies including the measurement of physiological, behavioural and production indicators of individual animals to improve management and welfare outcomes.

Public data: Data that has been collected by a government and is freely available for use by everyone.

Representational State Transfer (REST): A software architecture for web services.

Statistical Data and Metadata eXchange (SDMX): An international initiative for standardisation of statistical data and metadata.

1 Introduction

Food production is essential to feed the growing global population while agriculture is becoming more constrained by economic, environmental, social and cultural problems. Perrett et al. (2017, p. 1) stated "Digital technologies have the potential to fundamentally transform the way food and fibre is produced, traded and consumed". But Wolfert et al. (2017, p. 69) stated that "The future of Smart Farming may unravel in a continuum of two extreme scenarios: 1) closed, proprietary systems in which the farmer is part of a highly integrated food supply chain or 2) open, collaborative systems in which the farmer and every other stakeholder in the chain network is flexible in choosing business partners as well for the technology as for the food production side.".

1.1 Background

Global societies have become increasingly reliant on agricultural production (Kopittke et al., 2019). The origin of agriculture, that is to say the domestication of plants, was a slow evolution rather than a specific event. However, due to the effect it has had on humanity, it is often referred to as the First Agricultural Revolution and was agreed to have taken place approximately during the Neolithic, some 11,000 years ago (Childe, 1952). More recently, this has been revised to include the late Palaeolithic 23,000 years ago (Snir et al., 2015). Domestication of livestock, starting with goats, has been dated at 10,000 years ago (Zeder & Hesse, 2000). The next Agricultural Revolution took place between 1750 and 1880. Building on a culmination of changes that started during the late Middle Ages, it was a part of the Industrial Revolution (Cole, 1966). It saw the widespread adoption of a wider variety of crops, crop rotation, better livestock utilisation, improved farming equipment and increasing mechanisation. In recent years, the introduction and ever-increasing adoption of precision technologies, such as sensors, wireless networks, databases and software, have been described as yet another agricultural revolution (Lowenberg-DeBoer, 2015), which is also referred to as Agriculture 4.0 (De Clercq et al., 2018).

Food security has been defined as a "…situation that exists when all people, at all times, have physical, social and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO 2015, p. 53). Ehrlich and Harte (2015) suggested that another agricultural revolution is required to ensure global food security in view of a projected 30% increase in human population by 2050, emphasising that better agricultural practices must occur in conjunction with many far-reaching industrial and societal changes. Climate change adds further complications to this scenario (Skuce et al., 2013). The complexity of the situation highlights the importance of data (and the need for data interoperability), since solving these issues will require a multidisciplinary or integrated approach, not just within agriculture, but also across numerous related domains.

Livestock farming, which has been described as the largest land user on Earth, is subject to yet more layers of complexity (Herrero & Thornton, 2013). In addition to increasing concerns about the environmental impacts of meat production and sustainability (Salter, 2016), there are rising public concerns relating to the health, ethical treatment and welfare of farm animals. Proposed solutions to the meat production, animal welfare, and environmental impact scenarios include alteration to consumer behaviour. Such changes could be affected by increasing consumer ambivalence towards meat consumption through knowledge of production methods, animal welfare needs and animal sentience (Bratanova et al., 2011; Ruby & Heine, 2012).

It is necessary to satisfy the increasing information requirements for livestock producers as well as consumers, industry and regulatory bodies overseeing production. Consequently, there is a need for accurate and timely data collection, systems to efficiently store data and means to display such data in meaningful, contextualised ways. A suite of technologies generally known as precision agriculture has the potential to provide this information (Colditz et al., 2014).

The terms Precision Livestock Farming (PLF), Precision Livestock Agriculture (PLA) and Precision Livestock Production (PLP) are interchangeable, and can be described as the use of advanced technologies to gather information from individual animals about their physiological and behavioural status and measurement of production indicators, aiming at maximising production potential and early disease detection (Bewley, 2010). Precision Livestock Farming has also been described as a management tool for automatic monitoring that combines intelligent software (for example using artificial intelligence) and hardware such that information can be extracted from many sources of farm data (Berckmans, 2014). Smart farming relates to all agricultural pursuits, including livestock farming. It takes precision farming further by adding planning and control mechanisms to the automatic monitoring. Management support is aided by smart[1] decision support systems and the combination of internet-connected devices with other farming tools (Wolfert et al., 2017).

Despite the rising need for information from livestock producers, industry, consumers and legislators, and the technological improvements that allow increasing levels of on-farm data gathering, a number of factors present challenges:

[1] The words “smart” and “precision” are deliberately used as high level descriptors in this context.

System complexity

- High degree of heterogeneity in agricultural systems in space and time (Antle et al., 2016a)
- Complexity of interrelationships: environment (Provenza et al., 2013), sustainability (Eisler et al., 2014; Robertson, 2003), economics (Rolfe et al., 2016; Thornton & Herrero, 2001), coexistence with other land uses (Roxburgh & Pratley, 2015) and climate change (Scholten, 2015)

Economics

- The cost of investment in PLF technology and perceived lack of value of such investment (Banhazi et al., 2012; Ferrández-Pastor et al., 2016; Steeneveld et al., 2015; Tey & Brindal, 2012)
- Concerns that PLF research findings do not translate into measurable benefits for farmers (Bewley et al., 2015)

Social

- Farmers' resistance to change and new technology (Aubert et al., 2012; Eastwood et al., 2012; Pierpaoli et al., 2013)
- Lack of technical skills on farms, coupled with lack of easy to use PLF solutions (Banhazi et al., 2012; Jago et al., 2013)
- Farmers' concerns related to data ownership, privacy and security (Wolfert et al., 2017)

Technical

- The trade-off between accuracy and timing of sensor reading and battery life (Srbinovska et al., 2015; Swain et al., 2011)
- Communication limitations: available radio bands, trade-off between range and power requirements of transceivers (Karim et al., 2014; Polo et al., 2015; Reiser et al., 2016)
- Depending on the sensors in a deployment, many different things may be measured, therefore resulting datasets do not always match up by timestamp, time period, geo-location, geographical scale, or data type. Some measurements yield continuous data streams, whereas others are individual values (Mal-Sarkar et al., 2016)
- Data acquisition difficulties in agricultural environments due to size and layout of area and factors that interfere with radio signals (Reiser et al., 2016)
- The network topology has to match the application to work effectively (Anisi et al., 2014), and be optimised in terms of power usage (Wang et al., 2016)
- Sensor networks have to be maintained, either by way of regular inspection or through detection of failed sensors, which creates alerts for human intervention (Díaz et al., 2011)
- Robustness and fault tolerance of sensors can be challenging in an outdoors environment (Aqeel-ur-Rehman et al., 2014)

Data limitations

- Lack of data interoperability due to multiple formats, protocols and interfaces, closed and proprietary data formats (Antle et al., 2016a; Jones et al., 2016b; Nash et al., 2009)

- Lack of standardised protocols (Anderson et al., 2013; Dobos et al., 2015; Nikkilä et al., 2012)

Further data limitations emerged during this research:

- Geo-referenced public data has varying degrees of spatial resolution and currency and may therefore be limited at farm or paddock scale
- While there are large public data repositories relevant to agriculture, datasets may be of insufficient quality, lack metadata or cannot be accessed
- A perceived lack of FAIRness (data are findable, accessible, interoperable and reusable) in open data may hamper federation with private data to enhance decision support tools
- Metadata can vary between datasets or data catalogues, even if they conform to a published data standard
- Public data catalogues do not have uniform access methods or metadata provisioning, although they are increasingly supporting Application Programming Interfaces (APIs)

This research is primarily concerned with the last aspect of the challenges to PLF, namely the data limitations, where data includes private data collected on farms as well as research data and public data that is available to be used in PLF applications. Some factors are already bringing about improvements in this area, such as:

- The availability of free and open-source software and protocols for software development are increasing.
- Interoperable standards are under development (Tasdemir et al., 2011; Taylor et al., 2013).

- Web services (REST APIs) and other APIs suitable for PLF are available (Murakami et al., 2007).
- The development of suitable ontologies for agriculture is advancing (Nash et al., 2011).
- The amount of easily available public data that is useful for aggregation with farm data (Capalbo et al., 2016) is growing. Public data and their metadata are made available in searchable catalogues, often supported by APIs.
- Data custodians are improving data and metadata quality through standardisation and quality assessment.
- The need for data to be findable, accessible, interoperable and reusable has led to the development of the FAIR principles (Dumontier & Wesley, 2018; Wilkinson et al., 2016) and FAIR data quality assessments (Wilkinson et al., 2019). FAIR is emerging as a data standard in the agricultural domain as well (Levett et al., 2019).
- Public-private partnerships are emerging, as well as more open approaches to the exchange of private and public data. Concurrently, investment increases in research leading to the development of new models as well as new smart farming products (Antle et al., 2016a).

While these factors stem from initiatives and work undertaken beyond the PLF domain, the potential benefits are nonetheless significant for this domain.

The extensive livestock farming industry finds itself at the cusp of widespread precision farming technologies but has several challenges to contend with, of which data quality and standards stand out as the ones that need to be resolved. Firstly, this will help the industry to make better use of existing and future private and public data to support on-farm decision support and secondly, it will greatly assist in integrating livestock data into supply chains and other cross domain information systems and applications.

Against this backdrop, this study seeks to further the understanding of the current situation with regard to interoperable data standards and data quality in livestock farming data. The specific aims and objectives are outlined in the next section.

1.2 Aims and objectives

The literature suggests that provisioning data such that they are findable, accessible, interoperable and reusable will support the advancement of PLF. The FAIR data principles, which embody those qualities of data and associated metadata are emerging as a global data quality standard, which is supported by multiple FAIR assessment frameworks.

The apparent benefits of using public data to support PLF and other livestock decision support applications can only be realised if sufficient public data exists, is FAIR and is useful for an intended purpose. To determine the potential usefulness of public datasets to PLF and thus realise any opportunities, particularly related to grazing animal welfare, the current status of public and private data and standards in livestock farming must be understood.

The aims of this study are to understand the current status of data interoperability standards and public open data with respect to the extensive livestock farming industry and to identify any challenges as well as potential for advancement of PLF.

To further those aims, the objectives of this study are to:

- Review the literature related to PLF adoption in extensive livestock farming to identify challenges, particularly with respect to data collection and provisioning.

- Review the literature and existing PLF software to determine the status of decision support applications for extensive livestock farming.
- Investigate data interoperability standards within and beyond the livestock farming domain that could help advance PLF.
- Investigate the quantity and quality of public datasets that could inform livestock farming decision support, where quality metrics relate to FAIR principles.
- Investigate the quantity and usability of public datasets for a specific decision support application in extensive livestock farming, in form of a case study on livestock welfare.
- Develop tools and software to support data searches, quality assessment and data visualisation.

1.3 Research questions

During the review of the literature, data standards and software applications in precision livestock farming, research gaps were identified, and questions were raised. These form the basis for the following research questions.

1. What is the status of data interoperability for the precision livestock farming domain in Australia?
2. Where and how can public datasets relevant to decision support within livestock farming be found?
3. What is the quality of these datasets, and can their FAIRness be determined?
4. What are the opportunities and the challenges to the use of public datasets in informing or supporting animal welfare in extensive farming systems?

1.4 Thesis structure

Chapter 1:

The first chapter provides an introduction of this research, including the background, the aims and objectives, research questions, thesis structure and the contribution of this research.

Chapter 2:

Beginning with the theory that data interoperability standards are not well developed and used within the precision livestock domain, a review of the global literature is used to develop the research questions.

In addition to the literature, this review also included applicable data interoperability standards and precision livestock software. It was published in January 2019 as a journal article titled “The role of interoperable data standards in precision livestock farming in extensive livestock systems: a review” in the journal Computers and Electronics in Agriculture (https://doi.org/10.1016/j.compag.2018.12.007).

Chapter 3:

The methods used for this research are detailed.

Chapter 4:

A systematic review of public datasets relevant to extensive livestock farming is undertaken, which investigates the quantity and the quality of available public datasets. To facilitate this, a new methodology for systematic data reviews is developed, based on the steps involved in systematic literature reviews. This methodology is then used to determine the number and quality of datasets in the extensive livestock farming domain. This search for datasets includes the development of automated scripts to facilitate efficient retrieval of metadata from public Australian data repositories. The quality of data is measured against FAIR principles. To achieve this, a FAIR assessment is undertaken, which utilises an existing Application Programming Interface (API) and a script that tests each dataset against a set of FAIR metrics.

This chapter was submitted as a manuscript titled "Livestock data – is it there and is it FAIR? A systematic review of livestock farming datasets in Australia" to the journal Computers and Electronics in Agriculture in September 2020. The public repository containing the source code for the scripts was published and is available at https://doi.org/10.5281/zenodo.4057868.

Chapter 5:

A case study is presented to determine whether it is possible to use the search technique developed during the systematic review in a live application and whether sufficient public open data actually exists to inform a precision livestock application. The case study focus was on animal welfare in extensive agricultural systems of the Australian beef cattle industry. The dataset search for this chapter uses different criteria and search terms to Chapter 4.

This chapter was submitted as a manuscript titled "Can we improve livestock welfare with public data? An Australian case study" to the Journal of Applied Animal Welfare Science in January 2021.

Chapter 6:

A geospatial portal software application is developed which visualises the datasets which supported the animal welfare case study, to further test the usefulness of such datasets. A demonstration version of this portal can be viewed at http://phoebus.cerdi.edu.au.

Chapter 7:

The discussion of limitations and opportunities found with regard to open data within the livestock domain, and further opportunities arising from this study support a case for the adoption of interoperability standards.

Chapter 8:

The conclusions from this research are presented.

1.5 Contribution

1.5.1 Contribution within this thesis

Several contributions from this thesis will be of interest both in Australia and internationally with regard to PLF and the broader agricultural domain.

- Reviewed data interoperability standards within the PLF domain and in a broader context to determine the level of technology adoption and data interoperability maturity.
- The literature review in Chapter 2 has been published as a review paper in the journal Computer and Electronics in Agriculture (Impact Factor 3.858) in January 2019 (Bahlo et al., 2019). At the time of thesis submission, this paper has received 17 citations (according to Google Scholar).

- Developed a methodology to systematically find and review open datasets. The context for this development is livestock farming, however the same methodology can be applied within other domains.
- Developed strategies to query a variety of Australian open data catalogues to allow for the acquisition of data and metadata for the livestock domain.
- Developed open-source software scripts to retrieve metadata from open data catalogues to be used for the review of Australian livestock farming datasets, but also useful to automate the search for open datasets in other domains and geographies.
- The dataset search and assessment were written up as a manuscript and submitted to the journal Computers and Electronics in Agriculture in September 2020. At the time of thesis submission, it is still under review.
- Reviewed FAIR assessments and measuring the level of FAIRness of public data in the livestock farming domain in Australia.
- Identified the opportunities and barriers related to the use of public datasets to inform decision support in livestock farming through the use of a case study.
- The case study was written up as a manuscript and submitted to the Journal of Applied Animal Welfare Science (Impact Factor 1.122) in February 2021. To comply with the journal guidelines, the manuscript was limited to 8,000 words and supplementary information and data was submitted with the manuscript (Appendix 2 of this thesis). At the time of thesis submission, it is still under review.

- Developed a proof-of-concept animal welfare hazards map that displays public datasets.
- Made recommendations about data standards and FAIRness assessment in the livestock farming domain.

1.5.2 Other contributions and work undertaken during the candidature

A conference poster titled “Advancing data interoperability standards for livestock welfare and production systems” was presented at the 2016 Federation University Research Conference in Ballarat, Australia and received a commendation. The poster is available at: http://chrisbahlo.com/pdf/2016-ResConfPoster.pdf

The conference paper “Accessible farm animal welfare data: The role of interoperable standards in precision livestock farming” was presented at The International Tri-Conference for Precision Agriculture in Hamilton, New Zealand in 2017. The conference paper is available at https://doi.org/10.5281/zenodo.897205 and the presentation slides at https://s3-us-west-2.amazonaws.com/17acpa/Speaker+Permission/2D5-1ACPLF_ChristianeBahlo.pdf

Participation in GovHack 2019 as part of a team, which used public soil datasets to create a land use index. This project won the challenge “Visualising the soil quality of Victoria”. Project background and links to evidence of work can be found at: https://hackerspace.govhack.org/projects/ili_innovative_land_index

Participation in the Soil Cooperative Research Centre Visualising Australasia’s Soil (VAS) project researching public soil data in Australia. Using the techniques and scripts developed as part of the livestock dataset search in this thesis, a systematic search of soil datasets was undertaken. This work is not yet published. The VAS portal can be accessed at: https://data.soilcrc.com.au/map/about

Participation in GovHack 2020 as single entrant in the challenge “How might we create a citizen science experiment to support a better understanding of what is happening in the State of Victoria?”. The project “Animal Welfare Tracker” was a finalist and received a commendation. The project page with links to evidence of work and the conceptual software can be found at:

https://hackerspace.govhack.org/projects/animal_welfare_tracker

2 Literature review and development of research questions

This review encompasses literature related to data and interoperability standards in precision livestock farming, and where applicable, related domains. Additionally, the extent of the use of precision farming tools and technologies in livestock production and welfare is investigated. This review has been published as a journal article.

2.1 The role of interoperable data standards in precision livestock farming in extensive livestock systems: a review

2.1.1 Abstract

Livestock industries are increasingly embracing precision farming and decision support tools. As a result, sensors, weather stations, individual animal tracking, feed monitoring and other sources create large data volumes, much of which is used only for a single purpose. There are unrealised potential benefits of making on farm data interoperable and accessible and federating it with public data sources. We reviewed recent literature on precision livestock farming (PLF) technologies in relation to the use of public data, open standards and interoperability. Livestock farms produce rising volumes of disparate private datasets, reflecting a variety of information needs and technological opportunities, but typically lacking interoperable formats and metadata. These as well as large amount of accessible public datasets are currently underutilised in decision support tools. Demonstrating the use of interoperable standards and bringing together public and private data for decision support can enhance the value proposition and help lower barriers to the sharing and re-use of data. This review of interoperable standards in extensive livestock farming systems concludes that there is a need for a new type of geospatial decision support tool to prove

the value of shared data at farm scale (commercial benefit) and a regional scale (public good).

2.1.2 Introduction

The global livestock industry is facing increasing public scrutiny of the sustainability and environmental impacts of animal production (Salter, 2016) and in relation to the health, ethical treatment and welfare of farm animals (Hocquette et al., 2014; Robertson, 2003). While producers focus on maximising profitability in livestock enterprises, industry best practices, consumer expectations and legislation also demand that high standards of welfare are provided. In many countries, domestic laws and participation in international markets demands more compliance and associated record keeping (Nash et al., 2011; Nikkilä et al., 2012), that calls for technological solutions. Additional drivers for technology adoption are the scale of operations, declining staff to animal ratios, labour costs, focus on individual animal performance and the likelihood and consequence of disease outbreaks (Yazdanbakhsh et al., 2017). There is substantial potential to increase animal welfare, profitability and sustainability if technology adoption hurdles can be overcome, particularly in view of limited skilled labour and the increasing size of livestock operations globally (Blackmore & Apostolidi, 2011; Morris et al., 2011).

Technology is increasingly being applied to measure livestock production and welfare. Previous research in animal health monitoring using global positioning system (GPS) collars has shown that animal movement patterns can provide information on health status, for example, the prediction of worm burden in sheep (Morris et al., 2011) and wild dog predation events (Manning et al., 2014). In combination with motion sensors, even more behavioural information can be gathered (Ungar et al., 2018).

Technologies such as remote assessment of pastures (French et al., 2015; McEntee et al., 2013), walk over weighing (Brown et al., 2015; Richards et al., 2006), automated body scoring (Brown et al., 2015), matching lambs to their mothers (Morris et al., 2011), recording of grazing behaviour (Werner et al., 2018), prediction and monitoring of parturition (Dobos et al., 2014; Dobos et al., 2015; Neethirajan, 2017) are examples of smart farming technologies that provide production and welfare measurements.

Welfare indicators can also be monitored in different ways. For example, distress can be vocalised by animals or shown though unusual activity (Bokkers & Koene, 2001). Vocalisation could be measured via microphones, whereas activity could be observed and recorded using staff observations or surveillance cameras, with the interpretation of sounds and images to produce meaningful information. Similarly, animal condition is usually determined by weighing (either by walk-over automated systems or manually), but could also be estimated through alternative morphological measurements or automated image recognition (Catalano et al., 2016; Tasdemir et al., 2011). Therefore, decision support tools or applications for monitoring welfare indicators should have the flexibility to handle inputs from many sources and be able to raise alerts when conditions occur that are indicative of substandard welfare situations on farm.

Extensive livestock farming is characterised by grazing animals on large farms, managed with low labour inputs, often on rangelands, which make up 50% of the earth's surface and are unsuitable for other types of farming. Rangelands provide 70% of the feed for ruminant livestock worldwide (Derner et al., 2017). Despite their geographic size and economic importance, extensive livestock and rangeland farming systems lag behind intensive animal farming systems in the level of adoption of precision farming technologies and associated research (Roxburgh & Pratley, 2015). Multiple layers of complexity mean that extensive livestock systems face more challenges than intensive production systems with regard to the application of technology (Herrero & Thornton, 2013). Herds of animals can be large and may be dispersed over wide areas. This creates challenges in transmitting information collected by sensors, and may require deployment of wireless repeater stations (Neethirajan, 2017). Animals and weather can be harsh on electronic components, requiring robust design and high fault tolerance (Aqeel-ur-Rehman et al., 2014). Steep slopes or woody vegetation cover can interfere with the use of satellite positioning systems and wireless communications (D'Eon et al., 2002; Swain et al., 2008). Terrain also dictates animal distribution, travel routes and grazing patterns, and grazing in turn affects plant cover and composition (Ganskopp & Bohnert, 2009). Additionally, rangelands are often fragile, unpredictable and unstable in terms of productivity and need careful management to avoid land degradation and animal welfare problems (Roxburgh & Pratley, 2015). Technology has the potential to help manage these issues.

There is a rising demand for information from livestock producers, industry, consumers and legislators, and despite the technological improvements that allow increasing levels of on-farm data gathering, a number of challenges to sharing data for different purposes and with different stakeholders prevail:

- System complexity, recognised as a high degree of heterogeneity in agricultural systems in space and time (Antle et al., 2016a), and the complexity of interrelationships, such as: environment (Provenza et al., 2013), sustainability (Eisler et al., 2014; Robertson, 2003), economics (Herrero & Thornton, 2013; Rolfe et al., 2016), coexistence with other land uses (Roxburgh & Pratley, 2015) and climate change (Scholten, 2015; Skuce et al., 2013).

- The benefit-cost economics (or value proposition), that examines the cost of investment in PLF technology and perceived lack of value of such investment (Banhazi et al., 2012; Ferrández-Pastor et al., 2016; Steeneveld et al., 2015; Tey & Brindal, 2012), or the concerns that PLF research findings do not translate into measurable benefits for farmers (Bewley et al., 2015).
- The social dimensions, such as farmers' resistance to change and new technology (Aubert et al., 2012; Eastwood et al., 2012; Lima et al., 2018; Pierpaoli et al., 2013), and the lack of technical skills on farms, coupled with lack of easy to use PLF solutions (Banhazi et al., 2012; Jago et al., 2013).
- Technical issues around the sensors and their selection, for example the trade-off between accuracy and timing of sensor reading and battery life (Srbinovska et al., 2015; Swain et al., 2011), and sensor robustness and fault tolerance that can be challenging in an outdoors environment (Aqeel-ur-Rehman et al., 2014). Technical challenges of communication networks, including the available radio bands, the trade-off between range and power requirements of transceivers (Karim et al., 2014; Polo et al., 2015; Reiser et al., 2016), and the network maintenance, either by way of regular inspection or through detection of failed sensors, which creates alerts for human intervention (Díaz et al., 2011). The network topology has to match the application to work effectively (Anisi et al., 2014), and be optimised in terms of power usage (Wang et al., 2016).
- Data challenges, such as matching the various data streams by timestamp, time period, geo-location, geographical scale, or data type. Some measurements yield

continuous data streams, whereas others are individual values (Mal-Sarkar et al., 2016). There are data acquisition difficulties in agricultural environments due to the size and layout of farming systems and landscapes factors that interfere with radio signals (Reiser et al., 2016).

- Arguably, the most commonly cited challenge is the lack of data interoperability due to multiple formats, protocols and interfaces, closed and proprietary data formats (Antle et al., 2016a; Jones et al., 2016b; Nash et al., 2009), along with the lack of standardised protocols (Anderson et al., 2013; Dobos et al., 2015; Nikkilä et al., 2012).

As a contribution to the literature on the use of technology to increase animal welfare, profitability and sustainability, this paper reviews the uses, needs, advantages and limitations of livestock data in extensive livestock systems. In particular, the review highlights the opportunities of federating farm data with related publicly available data from the agricultural domain and other sources. Data interoperability standards have emerged as an important enabler in other industries (e.g. Brodaric et al. (2018); Dzale Yeumo et al. (2017); Lynch (2008)), and this review focusses on the adoption of, and potential contribution of interoperability standards for the use of public and private livestock data.

2.1.3 Data collection

Data collection for PLF is typically disparate, with a miscellany of data collected for diverse reasons over a variety of timeframes and a mix of formats. Since the introduction of digital agriculture, the volume of data has grown exponentially, much of it collected by sensors (Keogh & Henry, 2016). Data streams can include sensor data collected directly from animals, farm machinery or fixed farm monitoring sites, and are generally managed and routed via wireless sensor networks. Additional farm data can be collected from human observations, remote measuring and everyday farm record keeping.

Wireless sensors can be used to measure a variety of states and behaviours of animals. Examples of applications are animal tracking through GPS sensors (Swain et al., 2011; Taylor et al., 2011), assessment of foraging behaviour of grazing animals (Augustine & Derner, 2013), observation of behaviour to detect disease or parasite infestation (Falzon et al., 2013), monitoring activity of pigs (Cornou et al., 2011), and prediction of parturition (Dobos et al., 2014; Dobos et al., 2015).

Sensor applications consist of the actual sensor hardware, a small controller board, a battery and a communication device and may be housed in an enclosure that can be affixed to an animal. Sensors can be attached to animals by way of head or neck collars, ear tags, or leg bands. Neethirajan (2017) listed and reviewed wearable sensors for farm animals which can be used to measure health, drawing parallels to human wearable devices.

Virtual fencing systems extend the use of technology from passive sensors to being active devices that influence the grazing behaviour of animals. Such a system using GPS collars for herding animals was described by Butler et al. (2004) and has become commercially available more recently. In addition to containing and moving animals, it allows location and tracking as well as alerts when animals stray from designated areas.

Within the paddock, fodder measurement for the production and management of biomass in pastures and other feed sources is an important metric of a grazing system (Eastwood & Kenny, 2009). The accurate and timely measurement of available feed in the paddock is a prerequisite to efficient utilisation and therefore profitability (French et al., 2015), and the ability to provide adequate feed is a major welfare concern (Mellor, 2009). Superseding time-consuming and destructive manual measurements, fodder measurement is now possible through a variety of hand-held or vehicle-mounted devices, which measure pasture height, density and greenness with optical and other sensors. Technologies such as light detection and ranging (LiDAR) and measurement of greenness through normalised difference vegetation index (NDVI) can be used to estimate biomass (Schaefer & Lamb, 2016). Remote measuring and assessment of pasture biomass is also possible via aircraft and through satellite imagery. The variability of pastures both spatially and temporally add complexity to this available fodder measurement (McEntee et al., 2013). Schellberg et al. (2008) also noted that seasonal differences and selective grazing behaviour of ungulates, which also varies seasonally (Putfarken et al., 2008), can affect pasture composition over time.

Other farm-based sensors can also be deployed. These may measure local weather conditions, soil-moisture, water levels, livestock proximity to specific locations, vehicle movements and many other metrics. Depending on the sensors and their means of deployment, many different parameters may be measured. Some measurements yield continuous data streams, whereas others are individual values (Mal-Sarkar et al., 2016).

Sensor hardware can be heterogeneous within a sensor network, and several ad hoc sensor networks may exist within one system in which individual sensors may be added or removed at any time. Network topology has to match the application to work effectively (Anisi et al., 2014). A further consideration is the robustness and fault tolerance of sensors in an outdoors environment (Aqeel-ur-Rehman et al., 2014), but regardless of design and construction, sensor networks have to be maintained, either by way of regular inspection or through detection of failed sensors, which creates alerts for human intervention (Díaz et al., 2011).

However, digital agriculture and PLF need not rely solely on novel technologies such as sensors. Traditional farm records, often kept in accounting software systems, can also provide valuable information, especially when combined with the plethora of other data that can be amassed for any particular place in the landscape. Records of stocking numbers, animal treatments, purchases and sales, chemical inventories, weather records, farm accreditation records, and pasture treatments are examples of data that can be combined with satellite imagery and other sensor data to build up a rich picture of data that can inform farm profitability and animal welfare.

Data management therefore poses a number of challenges. The use of standardised data formats, exchange protocols and metadata, such as the suite of services offered by the Open Geospatial Consortium (OGC) has the potential make disparate data collections more manageable and usable (Botts et al., 2008).

2.1.4 Data management

Agricultural data is stored in a variety of current and legacy formats. For digital data, some of these formats are open, in the sense that their specification is known, while other data formats are proprietary (not open), which limits accessibility and interoperability. In some cases, proprietary data collections facilitate data export to open formats for re-use. In other cases, data is made accessible via web services or solely through proprietary interfaces. However, the lack of standardisation presents challenges to using data beyond its initial lifecycle, especially when federation or integration with other datasets is desired (Blank et al., 2013; Kruize et al., 2016; Murakami et al., 2007). In comparison, the storage and management of data using international interoperable standards has several advantages, which are summarised as follows.

The aggregation of multiple datasets from the same domain is simplified where a common standard is employed. Likewise, federation of data with data from other domains is facilitated, particularly when metadata is also standardised (OGC, 2016a).

Metadata is data about data; it gives meaning and context to data values and helps to organise larger volumes of data (Santos & Riyuiti, 2012). Further, it allows machines to understand data by providing models and removing ambiguity (Tolk et al., 2011). Standardised metadata using shared language definitions significantly adds to data interoperability. Such standards are developed and maintained standards organisation such as the Dublin Core Metadata Initiative (DCMI) and the International Standards Organisation (ISO). Notable metadata initiatives in the agriculture domain include the Agricultural Information Management Standards (AIMS), the Agricultural Metadata Element Set (AgMES), AgXML, AgroXML and Agrovoc, which is an agricultural vocabulary that has been published as a linked data set with external links to other vocabularies. The most recent model suite under development is rmAgro (Goense, 2017).

The use of standardised domain ontologies lends precise meaning to marked-up information and improves accessibility and discovery of that information (Ferrario & Kuhn, 2016). The discovery of data sets from various heterogeneous sensor networks can be difficult without the use of a semantic approach and suitable ontologies (Yoo & Harward, 2013). Semantic mark-up of information embedded in web pages enables discovery and re-use.

Regardless of the type of database, operating system or server, web services provide accessible interfaces via the Internet to applications, for example via REST[2] APIs[3] . Web services can serve data in XML or JSON format to any authorised application on demand. Interoperability and ease of access is improved if web services are implemented using standards, such as the suite of OGC standards (Nash et al., 2009). Accessibility of data is enhanced through the use of standard web services for retrieval. This also assures that data is operating-system independent and can therefore be accessed from any computer or device. The duplication of software development efforts is reduced, as subsequent re-uses of data and derived information do not require a transcription or translation. Adequate metadata and domain ontologies support this.

The resulting possibilities for combination of information can yield new insights. One example is data visualisations, especially in a geographic context, which benefit from open and interoperable standards (Jones et al., 2016b; Yoo & Harward, 2013). The use of visualisations can enhance the understanding of information for users and help toward technology acceptance (Van Hertem et al., 2017).

Agriculture has been a slow adopter of interoperability in information technology (Sawant et al., 2017), so it appears useful to investigate open data, standards and interoperability more broadly. The increasing connectivity of things in many domains such as manufacturing, health care, power grid management, traffic management, and many others brought about a rise in Machine to Machine (M2M) communication and the Internet of Things (IoT). The

[2] Representational State Transfer
[3] Application Programming Interfaces

need for common and interoperable standards was recognised early and has led to several cooperative initiatives.

OASIS, the Organization for the Advancement of Structured Information Standards was formed in 1998, being an expansion of the 'SGML Open' founded in 1993, where SGML means Standard Generalized Mark-up Language. It is a non-profit consortium for open standards in the "*global information society*" (OASIS, 2016). Standards were developed for the IoT, cloud computing, and numerous other domains.

PLF heavily relies on sensors for the capture of data from multiple sources on a farm. Sensors are rarely employed in isolation, usually there is system of sensors, often of several different types. For example, a PLF system could typically consist of soil moisture probes, temperature probes, proximity sensors, weight scales, radio frequency identification (RFID) tag readers, or watertank level sensors. Adding several such systems together creates a system of systems, adding to complexity and scale. Consequently, interoperability of system components is a necessity. In the longer term, the use of open standards has financial benefits and increases the longevity of information systems. This is because data and components have the potential be used and re-used for purposes beyond the original design or intent (Zyl et al., 2009).

Following an extensive review of studies that had collected data from GPS location devices on cattle, Anderson et al. (2013) recognised the challenge of collecting and federating animal tracking data with GIS data. In addition to the need for multi-disciplinary approaches to realise future research opportunities, they recommended the standardisation of protocols to aid such research and for livestock management purposes. It can be argued that the involvement of multiple disciplines in itself will necessitate an approach using interoperable standards.

Nash et al. (2009) recommended the use of geospatial web service standards which are being developed by the OGC. The OGC's mission is "*To advance the development and use of international standards and supporting services that promote geospatial interoperability. To accomplish this mission, OGC serves as the global forum for the collaboration of geospatial data / solution providers and users.*" (OGC, 2016b). Kubicek et al. (2013) described the use of the OGC's Sensor Web Enablement (SWE) and associated Sensor Observation Service (SOS), Sensor Planning Service (SPS) and Observations and Measurements (O&M) in developing an application enabling the geo-visualisation of sensor data. Data sharing in agriculture is the goal of the OGC's Agriculture Domain Working Group, whose scope includes "*everything geo-agricultural*" (OGC, 2016a). To date, no specific agricultural standards (i.e. agriculture-specific data schemas) have been published by the OGC. However, many of the existing OGC standards are applicable to data collection in agriculture, including PLF, and are widely being used (Phillips et al., 2014; Rafoss et al., 2010; Schaap et al., 2017).

In recent years, a number of international organisations have been working towards agricultural data sharing. The Global Open Data for Agriculture & Nutrition (GODAN) initiative started in 2013, supporting high level collaboration on open agricultural data sharing (www.godan.info). GODAN has several working groups, of which the Agriculture Open Data Package Working Group is the most relevant in this context. This group published an international open data charter, which promotes open data sharing and introduces the Agriculture Open Data Package Beta (www.agpack.info) which 'provides a roadmap for governments', suggesting policy areas in relation to open data in agriculture and giving examples.

Similarly, the Research Data Alliance's (RDA's) Agricultural Data Interest Group (IGAD)[4], also founded in 2013, is a working group promoting interoperability of global agricultural data within a research context. Within IGAD exist several other working groups dedicated to specific crop types and soils. Additionally, the Agrisemantics working group was formed in early 2017 to gather requirements to incorporate semantics into agricultural data to enhance interoperability.

Despite these initiatives, little work has been done in relation to livestock data. The World Wide Web Consortium (W3C) hosted a livestock data inter-change standard community group[5], established in 2013 by a group of NZ dairy, beef and sheep organisations. This W3C group was disbanded in 2014. However, several stakeholders in NZ, led by Rezare Systems (www.rezare.co.nz) are still pursuing the goal of livestock data standards, and published planning documents drafted by several workgroups on Animal ID and Life Data and Observations, Measurements, and Health (Rezare Systems, 2013). Subsequent work led to the development of the New Zealand Farm Data Standards[6], as well as an associated New Zealand Farm Data Code of Practice[7].

Farms are commercial entities that may not choose to release their collected data into the public domain. Privacy and ownership, security, and confidentiality of private data are areas of concern to farmers (Jones et al., 2016b). Commercial needs dictate that these issues have

[4] www.rd-alliance.org/groups/agriculture-data-interest-group-igad.html
[5] www.w3.org/community/livestockdata
[6] www.farmdatastandards.org.nz
[7] www.farmdatacode.org.nz

to be considered for all farm data, while making it accessible on an as-needed basis to authorised entities, or subject to conditions for open data or public use. Standards chosen for data collection and management must facilitate these needs (Broring et al., 2011).

Describing the issues of big data in agriculture, Wolfert et al. (2017) stated that while there are great opportunities, there are also potential threats to farmers in relation to data ownership, privacy and security. Hence there is a need to build trust, collaborate and form alliances to ensure that collected data is open, available, of sufficient quality and can be integrated with other sources. Capalbo et al. (2016) also recognised the need to respect data privacy and ownership when designing data infrastructure that combines public and private data.

Government agencies and other bodies collect data from many sources, many of which are freely available. Such public data can provide highly relevant context to on-farm data, and includes weather, soils, climate, market information and other sources (Antle et al., 2016a).

However, much of the geo-referenced public data has low spatial resolution and may be of limited use at farm or paddock scale. Additional considerations are the currency and veracity of public data, including the ongoing availability, update frequency and method of provisioning. Nonetheless, public datasets provide a rich source of information which is currently under-utilised in PLF applications, with the possible exception of weather data.

2.1.5 Precision farming and precision livestock farming tools and applications

Precision farming tools and applications have been developed for, and are successfully used for, many different purposes. It can be argued that a common goal of most precision farming applications is decision support, be it at farm level or at broader geographic scales. Capalbo et al. (2016) pointed out the differences between decision support tools (DSTs) at farm level and landscape-level. Many specific examples exist of farm-level DSTs, and are used by farmers, advisors and specialists (Jones et al., 2016a). At a landscape level, DSTs have been developed to assist in issues such as crop-change scenario evaluation (Tayyebi et al., 2016), plant disease diagnosis (Goodridge et al., 2017), climate-smart agriculture (Brandt et al., 2017) and sustainable agricultural intensification (Lindblom et al., 2016). These types of DSTs are for use by industry bodies or policy makers.

Examples of regional DSTs with a geospatial interface include the Digital Dashboard, developed by the CSIRO as part of the Digital Homestead Project (The Digital Homestead, 2015), the NRM Spatial Hub, which is collaborative project of the CRC for Spatial Information (NRM Spatial Hub, 2016), and the Precision Pastoral Management System (PPMS), a project of the CRC for Remote Economic Participation (CRC for Remote Economic Participation, 2016). However, livestock related applications remain underrepresented, and mainly exist in the form of farm-scale commercial solutions.

A wide variety of models are essential for the scientific study of agricultural systems, and of increasing importance for prediction and decision support systems in agriculture (Jones et al., 2016a). The newer generation of agricultural models aim at more accurate representation of the complex interactions on farms and within whole landscapes (Jones et al., 2016b). Model development relies on highly available, open and harmonised data, on collaboration between researchers and users, and need to be designed with modularity, interoperability and user friendliness (Jones et al., 2016a). Particularly with respect to livestock farming, improved models are needed to address heterogeneity on farm and to allow the inclusion of livestock data into larger models (Antle et al., 2016a). Visualisation of agricultural models is also an area in need of new developments (Janssen et al., 2016).

Open source and proprietary Geographical Information Systems (GISs) can be used in agriculture to combine, visualise and analyse raster based images (maps, satellite images) and vector based data represented by points, lines, polygons and other symbols. They enable modelling and interpretation of geo-reference agricultural data, e.g.: bug infestations investigation (Al-Kindi et al., 2017) or groundwater assessment for agriculture (Mehra et al., 2016). Spatial decision support systems (SDSS) use multi criteria decision making analyses (MCDM) in conjunction with geospatial data for planning scenarios, for example to determine land suitability for agricultural uses (Yalew et al., 2016), to explore different crop scenarios (Tayyebi et al., 2016), or to help plan agriculture in a climate context (Brandt et al., 2017). SDSSs for grazing systems and livestock are becoming available to assist farm level decision makers, but there is a lack of such decision support systems for broader geographic contexts.

The possibility of automated compliance checking in PA has been investigated by Nash et al. (2011), who recommended implementation of such systems using Extensible Markup Language (XML) based schemas and web services. Another example of automatic compliance checking, developed by Nikkilä et al. (2012) was prototyped as part of the EU FutureFarm project (Blackmore & Apostolidi, 2011). This system facilitated compliance checking across multiple layers of requirements, within geographic and temporal contexts.

Looking at existing precision farming tools and applications in a broader context, usability and data interoperability emerge as a common theme. Pierpaoli et al. (2013), who reviewed literature relating to drivers of precision agriculture, singled out ease of use and usefulness as the main incentives for adoption of precision farming (PF) technology, recommending specific precision farming tools, which hopefully become disruptive, thus leading to a greater adoption of PF. Jones et al. (2016a) reviewed agricultural software from a systems modelling perspective, listing modularity and interoperability as one of the key lessons.

2.1.6 Discussion

In reviewing the global scientific literature it is clear that there is a need for accurate, timely and interoperable farm livestock data and information, associated models and knowledge products.

PLF technologies enable the collection of data which can become meaningful livestock information at different societal, legislative and geographic levels, notwithstanding the challenges of varying scales of geo-referenced data and the information needs at different organisational levels (Joost et al., 2010). To date, there is a lack of use of smart farming technologies in extensive grazing systems (Ferrández-Pastor et al., 2016), but due to technology improvements, cost reductions, shifting attitudes to technology and the increasing value of, and need for, information, the level of on-farm animal measurements is set to rise substantially. However, to avoid a flood of data of limited use, it needs to be standardised, contextualised geographically and aggregated into information (Capalbo et al., 2016).

It can be expected that technology adoption and associated data collection in livestock farming will follow a similar learning curve to other industries and will need to resolve questions not just around technical issues including interoperability, metadata and standards, but also in relation to data ownership and custodianship. Emerging decision support tools tend to be specific to the needs of single livestock enterprises, thereby skirting the issue of interoperability and data ownership implications. However, the resulting isolated and inaccessible datasets limit the potential uses of private data collections as well as the ability of one software tool to share data with another. More research is needed in this area, not only on a technical level, but also with respect to formulating a value proposition for farmers (data owners), industry bodies, application developers and others (data custodians).

A complementary source of relevant information for livestock farming decision support can be found in data sets from a variety of public sources, which are currently largely ignored within PLF applications. Indeed, it can be argued that the bringing together of relevant public data source in itself will yield valuable information for the livestock industry. However, the use of public data sets beyond weather and climate information, appears almost non-existent within livestock decision support systems. This is somewhat surprising considering the number of public datasets that are available and accessible. Using Australia as example, extensive open data sources such as the National Map (Australian Government, 2017) and Research Data Australia (ADRC 2018) are just two of dozens of portals that illustrate the extent of the available public data catalogues. For any farm on the Australian continent, there are in excess of a thousand data layers that could be used to inform the agricultural industry.

So why is this rich source of public data ignored by the PLF industry? Although most of the public (open) data satisfies the FAIR principles, that is, data sets are findable, accessible, interoperable and reusable (Wilkinson et al., 2016), there are additional considerations. These involve data quality, geographic and temporal resolution, currency and data formats. For example, it may be necessary to perform calculations based on multiple geospatial layers, which may be impossible if available layers lack that information or do not provide it in a numeric format. Alternatively, data may exist, but it is out of date or has an insufficient spatial or temporal resolution. Additionally, there may be lack of consistency across larger regions, for example, adjoining government areas may not use the same frames of reference or comparable datasets for the same purpose.

It could be argued that there are a plethora of decision tools already available that can integrate data, however, research suggests that the on-farm uptake is low (Rose et al., 2016). Analyses of why this might be the case indicate that Australian farmers may initially use the tools, but revert to intuition for decisions, except for extraordinary conditions (McCown et al., 2012). Other studies in the dairy industry suggested that it takes considerable time to learn how to maximise the benefits of the technologies (Eastwood et al., 2012), or that there was no demonstrable economic benefit after adoption of smart technologies (Steeneveld et al., 2015).

Since the intention of data portals and decision support systems in PLF is to assist livestock producers and consumers, research is clearly needed to assess the value proposition for the end-user. These may be simple, but clear questions such as: how does federating data help the user make decisions? Make money? Make ethical choices? And does providing all the data change practices? Or change policy? Therefore it could be argued that the social architecture is equally important to the technical architecture in building interoperable data ecosystems (Box, 2017).

This leads to two overarching questions. Firstly, can available public datasets provide, or at least add to, the optimum breadth and depth of information for livestock decision support systems, and if so, at which geographic or temporal scales. Secondly, is it possible to motivate owners of private data to share their data for the common good, the value proposition being increased knowledge about their complex livestock farming environment and improved decision support tools in return for access to their data (or parts thereof)?

2.1.7 Conclusions

Combining private livestock farming data with public data will improve the output of agricultural models (Capalbo et al., 2016), but the challenge is to find ways to meaningfully combine these data sources at varying spatial scales, and resolve questions relating to data ownership, data quality, processing, analytics, and integration. The use of open platforms is expected to promote the development of solutions (Wolfert et al., 2017).

Users prefer information over data, and model outputs, i.e.: predictions and recommendations, over models, therefore technical solutions to the information needs of users should offer the output of predictive and decision support tools, supported by visualisations. The use of a cross-disciplinary approach that includes geographical information systems, sensor networks and standardised protocols is indicated to generate information useful for decision making (Antle et al., 2016b; Schellberg et al., 2008). The next logical step is the development of a geospatial portal that brings together available data sources by the use of interoperable standards. In future, this may also include the use of social media feeds and other data sources.

A rich set of queryable geospatial data has the potential to enable the development of new livestock decision support models. There is also potential for the use of machine learning algorithms to provide and refine predictive functionality.

Precision farming technologies will increasingly provide measurements via on-animal sensor readings (Morris et al., 2011). However, the provision of relevant context through federation with related geographic and environmental information will add value to such animal data. Using interoperable data standards and web services, this type of information can be provided, not merely to offer context, but to contribute to decision support tools for the livestock industry. Gaining greater value and insights from combining livestock data with other information benefits producers, industry and regulatory bodies (Taylor et al., 2013).

2.2 Epilogue

The literature review sought to determine the current situation with regard to PLF technologies in extensive livestock farming, particularly with respect to interoperable data standards. Extensive livestock farming is a subset of the livestock farming domain, which is a subset of agriculture. While geographically and economically significant in food production, the expectation at the outset was that technology adoption and supporting specific data standards would not be on par with the whole of the agriculture domain. The review of literature, data standards and existing PLF applications showed that this is indeed the case. Therefore, the review extended, where necessary, into broader domains to find applicable data standards that may contribute to data interoperability and reuse within the extensive livestock domains. The findings from this extended scope provided a better understanding of the challenges and opportunities for applying PLF to livestock in extensive grazing environments.

Subsequent to the publication of the literature review, new studies have sought to further the use and reuse of data in PLF. Fote et al. (2020) proposed a new knowledge-base management system for PLF to assist with decision support at the farm. However, while the authors note that most PLF systems are not interoperable, they do not specifically address interoperability and data standards. Another conceptual big data approach is introduced by

Perakis et al. (2020), which includes several PLF demonstrators. Data interoperability as well as semantic mark-up and reusability are mentioned as core concepts.

García et al. (2020) reviewed the use of machine learning (ML) in PLF and identified data management as one of three main areas of concern to adopting ML. Another review related to farm management information systems also pointed to the lack of data standards and interoperability as an obstacle (Tummers et al., 2019).

Looking more broadly, ongoing development and increasing adoption of tools and data standards that improve workflows, standardise data access and facilitate linkages between data repositories are likely to benefit the livestock farming domain. This includes open source software, open API standards, semantic web query tools, linked data in conjunction with graph databases, data vocabularies and new OGC services.

The unwillingness of farmers to share their data was briefly touched in in the discussion and still presents an ongoing challenge. (Wiseman et al., 2019) suggest that this is partially due to a lack of existing legal and regulatory frameworks. While there are complex and related personal reasons for farmers' reluctance, the crux of the matter is a lack of trust of farmers in those entities they may share their data with, which is also the central argument of Jakku et al. (2018). How this can be resolves is the subject of ongoing research and may end up being a combination of education, legislation and value propositions.

The significance of interoperable data standards within PLF is a recurring theme in the literature around all PLF applications across the broad agriculture domain. The degree to which these standards are adopted, and how this translates to usable available datasets for decision support, particularly in the extensive livestock industry, will need to be answered.

3 Research methods

This chapter outlines the methods for this research, and how they relate to the research questions. In addition to the methods listed here, the chapters that have been published or submitted for peer review to journals have their respective detailed method sections.

The methods designed to answer these research questions are outlined in Figure 3.1 - Mapping methods to research questions and explained in further details in the following sections of this chapter.

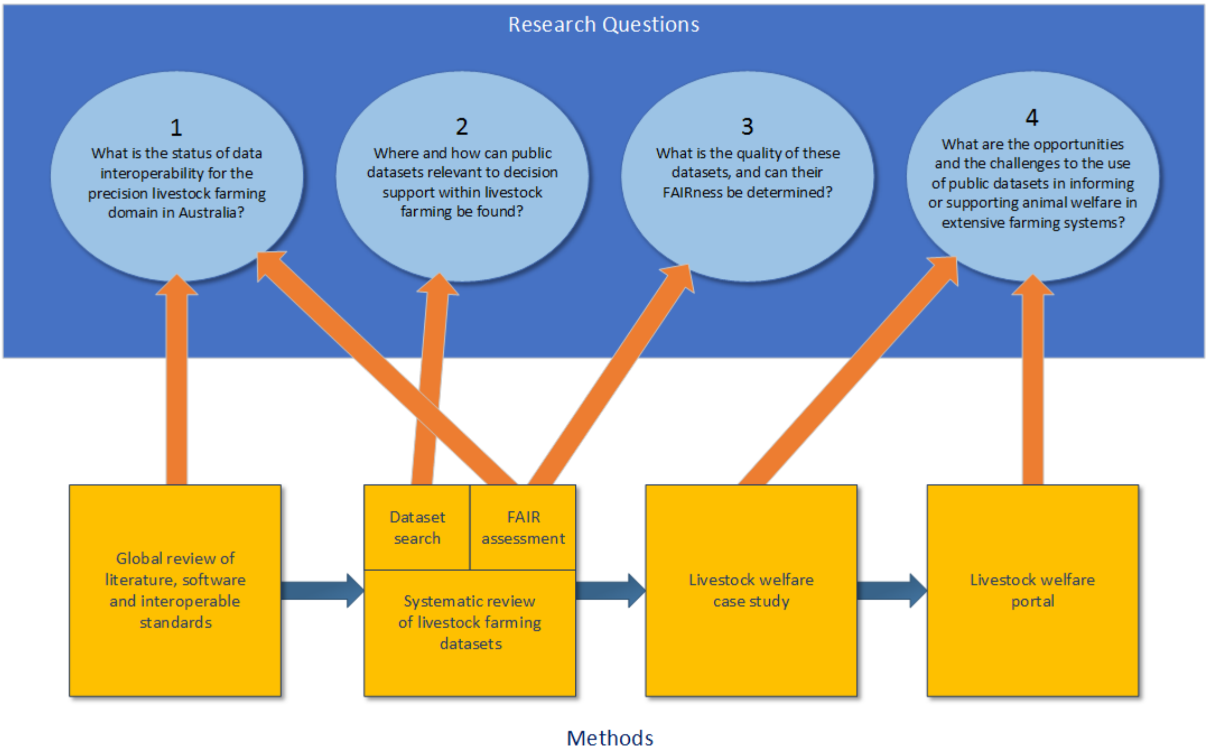

Figure 3.1 - Mapping methods to research questions

3.1 Research boundaries

This research is focused on the extensive livestock farming domain within Australia. The literature review is global in scope, while the systematic review of public datasets and the case study are limited to Australia.

3.2 Systematic domain data review and assessment

To answer questions from the literature review related to the amount and quality of available public datasets for extensive livestock farming a search of public data catalogues and a quality assessment of datasets are necessary. To facilitate this, a novel methodology for a systematic dataset review is designed and tools and techniques are developed. Firstly, public data catalogues are searched via automated scripts, followed by an assessment based on FAIR principles is undertaken. FAIR is one of several data quality assessment frameworks, it was chosen because it has gained a lot of traction and is well documented (Mons et al., 2020), and several FAIR assessment tools are available (FAIR Data Maturity Model WG, 2019).

The methods involved steps to identify data catalogues, determine search terms, identify and test API endpoints (if available), write scripts to query the endpoints and collate the results into a spreadsheet for sorting and searching. The scripts were written in PHP (with the exception of one in JavaScript) and can be run within a web browser to allow the user to enter search terms and set some search options. The scripts use curl requests and parse the APIs' JSON or XML output and display tabulated result listings for further analysis. After elimination of duplicates, the final set of 419 datasets were subjected to a FAIR assessment, which was also done via an automated script, using the FAIR Evaluation Services API. The detailed methods for the search via automated scripts and FAIR assessment are documented in the methods section of the submitted paper (Chapter 4). The API endpoints used for the systematic search and details of the FAIR metrics applied for testing are listed in Appendix 1. The FAIR metrics tests selected for the FAIR evaluation were a broad set of general metrics available, as no domain-specific tests are currently available.

The software tools used for the systematic dataset search and assessment are listed below:

- Postman App: to test API interfaces
- Sublime Text Editor: to write software scripts, for parsing and formatting of JSON and XML and for text searches of API output during script development
- Chrome web browser: to run software scripts
- Chrome developer extensions: for testing of software scripts
- Open source programming languages PHP and JavaScript: to build the custom scripts that query various APIs
- Data visualiser built with JavaScript and the d3.js library: to visualise relationships
- Data search software scripts that were developed: to find datasets and parse metadata
- Microsoft Excel spreadsheets: for collation of search results as well as sorting and filtering, and to produce charts

3.3 Case Study

The systematic dataset review in the previous section is designed to be broad and looks at data quality through the lens of the intrinsic data quality, while the case study is limited to a narrow topic but considers the usefulness of datasets as well as the data quality.

The case study seeks to test the assertion that sufficient public data exists for a specific livestock farming use case. The literature review identifies animal welfare as a topic of particular interest to the livestock industry, therefore it is selected for the case study. An attempt is made to find sufficient amounts of data to build an animal welfare risk map for welfare challenges that may arise from the environment.

The case study uses source code from the scripts developed in the data search but goes one step further to test if the metadata is sufficient to display meaningfully on a map and potentially be of use to farmers to make decisions for animal welfare. The methods used in the data search and subsequent steps are detailed in the submitted journal article (Chapter 5).

The use case chosen is within the stated scope of the project, addressing only extensive livestock farming. Further, it is limited to beef cattle. The geographic bounds of the case study are limited to Australia.

3.4 Conceptual grazing animal welfare portal

The result of the dataset search and analysis from the previous section are used to develop and populate a conceptual geospatial animal welfare portal. This is a further test of the potential usefulness of public data in informing welfare-related decision support for livestock farming. The specific methods are detailed in Chapter 6.

4 Public dataset search and quality assessment

The literature review identified the potential benefits of using public datasets to support decision making in precision livestock farming, but left open questions related to both quantity and quality of suitable public datasets for this domain. To help in answering these questions, a systematic dataset review is necessary. A review of the literature found no established methodology for conducting such a systematic dataset review, therefore a novel methodology is designed. This is based on systematic literature reviews but modified to work with datasets as opposed to publications. The second contribution arising from the dataset search and review is the development of software scripts to facilitate efficient automated querying of public data catalogues. These scripts are released as open source for re-use and modification. The result of the dataset search is a set of candidate datasets that are subsequently assessed on the basis of FAIR principles via a third-party API, which is also performed via automated scripts.

4.1 Livestock data – is it there and is it FAIR? A systematic review of livestock farming datasets in Australia

4.1.1 Abstract

The global adoption of the FAIR principles for scientific data: findable, accessible, interoperable and reusable, has been relatively slow in agriculture, compared to other disciplines. A recent review of the literature showed that the use of precision farming technologies and the development and adoption of open data standards was particularly low in extensive livestock farming. However, a plethora of public datasets exist that have the potential to be used to inform precision farming decision tools. Using extensive livestock farming in Australia as example, we investigate the quantity and quality of datasets

available via a systematic dataset review. This systematic review of datasets begins with a search of open data catalogues and querying these to find datasets. Software scripts are developed and used to query the Application Programming Interfaces (APIs) of many of the large data catalogues in Australia, while catalogues without public APIs are queried manually via available web portals. Following the systematic search, a combined list of all datasets is collated and tested for FAIRness and other quality metrics. The contribution of this work is the resulting overview of the state of open datasets within the livestock farming domain, as well as the development of a systematic dataset search strategy, reusable methods and software scripts.

4.1.2 Introduction

At the current time, there is more agricultural data being collected than at any previous time in history, much of it through the adoption of precision agriculture, sensor technologies and digital agriculture in general (Wolfert et al., 2017). These agricultural data are stored in a variety of databases on disparate computer systems, in both the private and public sectors, with an increasing volume in the private sector (Antle et al., 2016b). It is recognised at all levels, from international organisations to individual farms, that there would be benefits in bringing these data together in a seamless and standardised way for improved decision support (GODAN 2013). In Australia for example, it has been estimated that adoption of digital agricultural agriculture could result in a $20 billion (25%) increase in agricultural production, of which approximately $6.5 billion would be in extensive livestock agricultural systems (Leonard et al., 2017).

Australian agricultural data has been historically collected by federal and state government agencies, including research institutions and universities. These data comprise a wide range of agricultural production statistics and agricultural science data associated with research, investigations, trials and the development of new agricultural areas or industries. Some of these are published as open data, which “can be freely used, modified, and shared by anyone for any purpose” (Open Knowledge Foundation, n.d.). Other datasets are closed, that is, they are commercially sensitive or contain private information and are therefore not accessible. Yet other data are neither sensitive nor private, and could be published, but are not in digital format, or findable on the Internet. Lastly, there are increasing amounts of data from sensors that are not yet generally available or accessible on the web.

In the private sector, data has historically been collected through agricultural research in companies supplying farm chemicals, animal health products and new plant varieties, for example. In more recent times the development and adoption of precision farming technologies contribute to the growing volume of data, much of it collected on-farm by agronomists and farmers. Sensor technologies such as yield monitors, machinery performance monitors and soil moisture probes have become common, although such technology is still expensive and not well integrated with other precision farming technologies, leaving questions of potential benefits unanswered (Klerkx & Rose, 2020).

Modern technological and communication infrastructure improvements are enablers of information collection and distribution. In parallel, there are factors that exert pressure on the industry, governments and scientists to seek out information, be it to gain new insights, create models for predictive purposes, for management decisions, or to satisfy reporting requirements (Wolfert et al., 2017). The development and adoption of interoperable data standards within the livestock farming sector is highly desirable to enable the use and reuse of datasets to facilitate those goals, but it is very limited so far (Bahlo et al., 2019). Also, such datasets need to be findable and of sufficient quality to suit any given use case. While the benefit of sharing agricultural data across the public and private sectors has been explored (Antle et al., 2016a), the value proposition for the end-users is not always obvious (Dahlhaus et al., 2018).

There has been a lack of methodologies for the selection and quality assessment of datasets in livestock farming as evidenced by the lack of literature. However, looking beyond this narrow domain, several examples of applying quality metrics to open datasets exist, such as the automated Open Data Portal Watch (ODPW), which measures aspects related to existence, conformance and openness of open dataset metadata (Kubler et al., 2018; Neumaier et al., 2016). Other international data quality assessments rely on manual measurements and include the Global Open Data Index[8] for government data worldwide, the Open Data Monitor[9] for European datasets and the Open Data Maturity Model[10] published by the Open Data Institute (ODI). Open data can be also be assessed via the 5-star scheme that is based on Sir Tim Berners-Lee's linked data concept[11] or using one of the several available tools for assessment of FAIR principles[12], which are based on the idea that data management best practices can encourage the discovery of knowledge, and promote innovation through integration and re-use of existing data (Wilkinson et al., 2016). Making data findable, accessible, interoperable and reusable (FAIR) is now a high priority for government and research institutions alike, driving the demand for better data management. There are still challenges around data classification and persistent identifiers,

[8] https://index.okfn.org/
[9] https://opendatamonitor.eu/frontend/web/index.php?r=dashboard%2Findex
[10] https://theodi.org/article/open-data-maturity-model/
[11] https://5stardata.info/en/
[12] https://www.force11.org/group/fairgroup/fairprinciples

especially in relation to scientific data (Parland-von Essen et al., 2018), but there is consensus regarding the need for adoption of FAIR data principles (Dumontier & Wesley, 2018; Stall et al., 2019). FAIR principles can be used to measure the quality of open datasets and to develop metrics which can be used to measure FAIRness (Dumontier & Wesley, 2018) and indeed several FAIR assessment methods have been developed by independent parties (FAIR Data Maturity Model WG, 2019).

The intent of this chapter is two-fold. Firstly, it seeks to determine the availability and quality of public datasets in the extensive livestock farming domain in Australia. Secondly, the intent is to present a methodology to find and assess datasets that is universally applicable to undertake a systematic review of data (cf: literature). It details specific methods that were developed for querying a variety of open data catalogues and ranking the found datasets according to the FAIR data standards. While this chapter focuses on a specific data domain in Australia, the methodology may also work for open datasets in other domains or geographies.

4.1.3 Systematic review of datasets

Since no guide could be found to undertake a systematic review of published data, this investigation broadly follows the guides for a systematic review of published literature as outlined by Koutsos et al. (2019, p. 109), as seen in Table 4.1:

Table 4.1 - Systematic dataset vs systematic literature review steps

Step	**Systematic dataset review**	**Comparable steps of literature review protocol**
1	define the questions to ask	scoping

2	define inclusion and exclusion criteria	planning
3	determine method	identification search process
4	search for relevant data	screening articles/data
5	extract metadata	screening articles/data
6	Remove ineligible and duplicate results	eligibility assessment
7	assess data quality	eligibility assessment
8	present and analyse results	interpretation, presentation

4.1.3.1 Definition of question

Using extensive livestock farming in Australia as a case history, where and how can public datasets relevant to the domain be found, and is it possible to measure their quality in terms of FAIRness?

4.1.3.2 Inclusion and exclusion criteria

The dataset search included Australian datasets related to extensive livestock farming; any search results related to intensive livestock farming or outside this geography were ignored. A number of relevant search terms were chosen, which include broad terms as well as names of farm animals and some common inputs and outputs from livestock production systems. This list is not exhaustive, but represents terminology most commonly used in livestock farming and expected to yield the representative cross-section of search results. These are listed below, together with a reason why these were chosen.

- livestock: word used to refer to several species of farm animals
- grazing: general term referring to raising livestock on pastures

- cattle: commonly raised livestock species
- sheep: commonly raised livestock species
- wool: one of the major outputs from sheep production
- meat: one of the major outputs from livestock production
- pasture: the main feed base for livestock production
- fodder: hay, grain and other supplementary feeds are used for livestock when pasture growth is low, which can be normal seasonal or due to exceptional circumstances such as drought, floods or fires

Although there are other search terms which are relevant and could be used, be it different livestock species, or classifications, we chose these broader and more common terms for an initial review, which aimed to obtain an overview of datasets available for the extensive livestock farming domain. Searches for more specific terms, for example "heifer", "bull" or "ram" were found to yield too few results in test searches, and in all cases, keywords in those datasets included the broader terms. Searches for specific locations or time periods were out of scope.

4.1.3.3 Method

Since there was no precedent of a systematic review of datasets found in the literature, the following method based on the guidelines for systematic literature review (Koutsos et al., 2019), was designed and includes the following steps:

- Identify potential sources of datasets
- List known national and state and territories open data repositories and catalogues
- Conduct a search of government and industry bodies related to livestock farming and identify those that provide open data

- Determine how datasets and their metadata are provisioned within catalogues
- Where possible, write scripts to harvest information about open datasets via APIs
- Where no API is available, attempt to bulk download, export or scrape information about datasets
- Where no automated or bulk download facility can be used, obtain information about datasets manually
- Collate the information and filter for duplicate and irrelevant datasets
- Choose a suitable FAIR assessment
- Assessment of dataset quality, including FAIR principles
- Analysis of results

The term catalogue is used in preference to repository, as most datasets are hosted external to the server hosting the catalogue database. The term catalogue is also used in preference to resource, to avoid confusion with dataset types, which are referred to as resources in several data catalogues.

4.1.3.4 Search

As a first step, well known data catalogues were identified. For Australian government data sources, a summary of resources is available[13]. Those relevant to agriculture include the Bureau of Meteorology Climate Data Online, Australian Bureau of Agricultural and Resource Economics (ABARES) data tools, Australian Government open data repository (data.gov.au) and Geoscience Australia Spatial Data Catalogue. Additionally, every Australian state and territory has an online open data repository. Other known providers of data related to livestock are the Commonwealth Scientific and Industrial Research Organisation (CSIRO),

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[13] https://www.australia.gov.au/information-and-services/it-and-communications/data

Australian Research Data Commons (ARDC) Research Data Australia (RDA) and Meat & Livestock Australia (MLA).

Using an Internet search for "livestock industry association" as entry point, a listing of industry bodies, government agencies and related organisations was compiled, both at national and state or regional levels. Many of the webpages for these bodies contained lists of links to related organisations, which were also added to the list, until no further relevant organisations could be discovered. Out of the resulting list of 47 organisations only two were found to host public datasets, and these had already been identified for a dataset search.

A query of the Google Dataset Search[14] for "livestock Australia" identified two additional data catalogues, which were included in the list of catalogues to search. This included Figshare[15], which is a data publishing tool widely used by Australian universities and two international research data repositories, being Data Dryad[16] and Zenodo[17].

Additionally, during a search for FAIR data standards and assessment tools, FAIRsharing[18] was identified. This site is not a catalogue of datasets, but rather a catalogue of databases as well as standards and policies which uses a collaborative approach (Sansone et al., 2019). While unable to find any additional datasets or data catalogues, it is of interest that ten data standards were tagged for livestock, although none of these were published by Australian organisations.

[14] https://toolbox.google.com/datasetsearch
[15] https://figshare.com/
[16] https://datadryad.org/search
[17] https://zenodo.org/
[18] https://fairsharing.org/

Table 4.2 - The list of 16 candidate catalogues for dataset searches

Name	Portal
Australian Government data.gov.au	https://data.gov.au/
Data Vic	https://www.data.vic.gov.au/
Data.NSW	https://data.nsw.gov.au/
Queensland Government Open Data Portal	https://www.data.qld.gov.au/
Data.SA	https://data.sa.gov.au/
data.nt.gov.au	https://data.nt.gov.au/
data.wa.gov.au	https://www.data.wa.gov.au/
Open Data Portal dataACT	https://www.data.act.gov.au/
Tasmanian Government the List	https://data.thelist.tas.gov.au/
CSIRO Data Access Portal	https://data.csiro.au/dap/home?execution=e1s1
Research Data Australia	https://researchdata.ands.org.au/
Meat & Livestock Australia	https://www.mla.com.au/
Australian Bureau of Statistics	https://www.abs.gov.au/Agriculture
Figshare	https://figshare.com/
Dryad	https://datadryad.org/search
Zenodo	https://zenodo.org/

The final list of catalogues shown in Table 4.2, was checked for the presence and type of APIs to automate a dataset search if possible, or whether searches need to be conducted manually or by some other method, for example an export of search results found in a portal.

4.1.3.5 Extract metadata

All listed catalogues have searchable online portals. A common problem is the lack of display options related to number of results per page, meaning that it is difficult or impossible to see all results on one page. Secondly, only a minimum of information is shown in the result summary, which necessitates navigating through to individual datasets to determine relevance. It also reduces the possibility of scraping data from the pages to obtain the entire result set. However, in some cases the portal allowed alternative methods to obtain the search results. The Tasmanian Land Information System (LIST) data portal[19] has advanced search facilities and allows search results to be exported in several formats, of which the comma separated values (CSV) format was the most useful for the purposes of further analysis. On the other hand, the website of the Australian Bureau of Statistics (ABS) has an advanced search to refine the full text search of contents, filter by content and publishing date and apply sorting, but it does not offer filtering by keyword.

All but four catalogues have public APIs that can be queried programmatically. The most commonly used data catalogue API was found to be Comprehensive Knowledge Archive Network (CKAN), followed by OpenAPI, both of which are open source projects. CKAN is dedicated data repository software, while OpenAPI is a widely used open standard for APIs. Additional APIs found were Magda, the getRIFCS API and Socrata API, all of which are dedicated data catalogue applications. Of those without public APIs, the Australian Bureau of Statistics is in the process of developing one (Australian Bureau of Statistics, 2020).

Some public facing APIs require an access key or have token-based authentication for API access, which has to be requested. On the other hand, multiple API endpoints are offered by some data portals, for example the ARDC's research data portal. In such cases, it is necessary to choose the most suitable endpoint to yield the data that is required. Also, the online documentation suggests that some APIs are no longer developed in favour of newer

[19] https://www.thelist.tas.gov.au/app/content/data/

implementations or versions, and where that was the case, the newer version was used to retrieve datasets from the catalogue, to ensure that the scripts developed are useful in future.

Data catalogue APIs return JavaScript Object Notation (JSON) or Extensible Markup Language (XML), which can be parsed via an external application. The most common ones found in Australia were CKAN and OpenAPI, whereas data.gov.au, the largest catalogue, uses the Magda API[20]. The ACT government and some Australian city councils use the Socrata API[21], which is a commercial government data discovery platform. Datasets using this platform can all be found via the Open Data Network[22] portal and the associated API endpoint. This data platform is used widely in the United States of America, but only three Australian urban government agencies are using this platform, therefore a script to harvest this portal was not undertaken. However, the ACT data catalogue was manually queried via the official online portal.

4.1.3.5.1 Operational challenges

The national open data catalogue, five of the eight open data catalogues of the Australian states and territories, and two other catalogues had public facing APIs that can be queried directly, and programming scripts were written to retrieve results. The remaining open data catalogues only had a web interface to search for datasets, which made the search process less efficient and relied on more manual work. For these catalogues, the search terms were manually entered, and the information retrieved from the relevant sections of the search results pages. While the development of automated scripts took some time, this approach

[20] https://data.gov.au/api/v0/apidocs/index.html
[21] https://socratadiscovery.docs.apiary.io/#
[22] https://www.opendatanetwork.com/

offered times savings due to the ability to reuse the scripts multiple times. Furthermore, these scripts are of use for future dataset searches. On the other hand, the lack of public facing APIs in data catalogues not only slows down the search and metadata retrieval, but also means that the same effort has to be expended for every data search.

As data.gov.au has the largest number of datasets (91,058 as 30 June 2020) and a public facing API, this catalogue was first searched by script, followed by the CKAN catalogues. Several scripts were developed to achieve this and eventually merged into a single script that retrieves metadata from the Magda API and the CKAN APIs. The result set showed numerous duplicates; therefore, logic was added to compare internal identifiers to mark duplicates found within those catalogues. This process was made more difficult due to the fact that internal catalogue identifiers didn't match up across catalogues, and it was necessary to extract identifiers from concatenated resource identifiers and organisation identifiers or use resource identifiers that are part of URLs.

Additional scripts were used to query the other available catalogue APIs from CSIRO and RDA and to access the MLA API. Unlike Magda and the CKAN APIs, these produce XML rather than JSON. It would be possible to combine all these searches into a single script; however, the additional development effort was not considered worthwhile for the purposes of this systematic dataset review. Also, some catalogues had to be queried manually, so at the conclusion of the dataset search, the results were collated in a spreadsheet for further processing.

Metadata was found to be variable in structure and content. For example, some catalogues did not provide information related to distributions, others showed no keywords. Catalogues like Magda and those provided by RDA and CSIRO appeared to be the most mature in terms of providing metadata, and some attempt was made to rate dataset quality, but such ratings only apply within a catalogue and cannot be used to compare datasets between catalogues.

4.1.3.6 Removal of ineligible and duplicate results

An initial overview showed that search results included many false positives, as they are obtained from full text searches performed on all fields in each record in the respective catalogue databases. For example, searching for “sheep” will find “Sheep creek” in an irrelevant dataset from outside the domain. However, this illustrates the difficulties of searching for datasets. Some web data portals allow the selection of specific data providers, keywords or categories to further refine search results. Where we directly queried the catalogue APIs, we were limited by their inbuilt query capabilities. We found that the Magda API, which underpins data.gov.au does not support keyword search, whereas the CKAN API, which is the basis of many other data catalogues, does. However, this is limited as it only returns literal results and exact case matches. While it is possible to pass a list of keywords as keyword query, it is still impossible to find keywords that were not exact matches. Therefore, a case-insensitive, partial match filter was added to the scripts.

False positives also occurred where the key word is also in other domains, for example the term “grazing” is used in ocean science as well as in the livestock farming domain. These were removed by filtering on the basis of the publisher.

Some catalogued datasets were found to have no keywords. These datasets will show up in a global search (which checks all fields in the database), but they will not show up when a filter is applied to the keywords field. The implication is that relevant datasets may be missed in automated searches. On the other hand, including all datasets with blank keyword fields may yield too many false positives. Another issue related to key words searches (both in web portals and API searches) is when the key words are too specific, for example if a research dataset about parasitic worms in sheep uses “ovine nematodes” then a keyword search for sheep will not return this dataset. This is a problem inherent in the choice of keywords for a dataset, not a problem with search algorithms or data access provisions. It means, however, that it may be useful to consider searching for terms not just by keyword, or to use more specific keywords.

To avoid the problem of too many results (not using keywords) or not enough results (keywords too specific), a strategy was developed when using API search scripts and manual searches as follows: the initial search was run on the entire catalogue, that is, all fields. The script then ran a text-insensitive search for the keyword anywhere, even as part of a word, within the keyword field of each dataset. The second step to refine the result set was to use spreadsheet filtering to manually remove irrelevant datasets belonging to other domains. While it would be possible to add this processing to the scripts, it was not known in advance which words to filter for to avoid such datasets. Where datasets were obtained manually, irrelevant datasets were excluded as they were identified.

4.1.3.6.1 Datasets found for each of the search terms

The result set of the dataset search using the method described above is shown graphically in Figure 4.2. This set includes all datasets found and shows relationships between search terms and catalogues. As expected, duplicates occurred across the different search terms. For example, datasets about sheep were also found by the query looking for livestock or grazing. Indeed, often several of the search terms were found within the keywords for a single dataset. Note that in the graph shown, a relationship is included for each search term in every catalogue because at this stage, duplicates due to search terms had not been eliminated. The numbers of datasets are shown in brackets and the thickness of the joining lines also reflects the number of datasets.

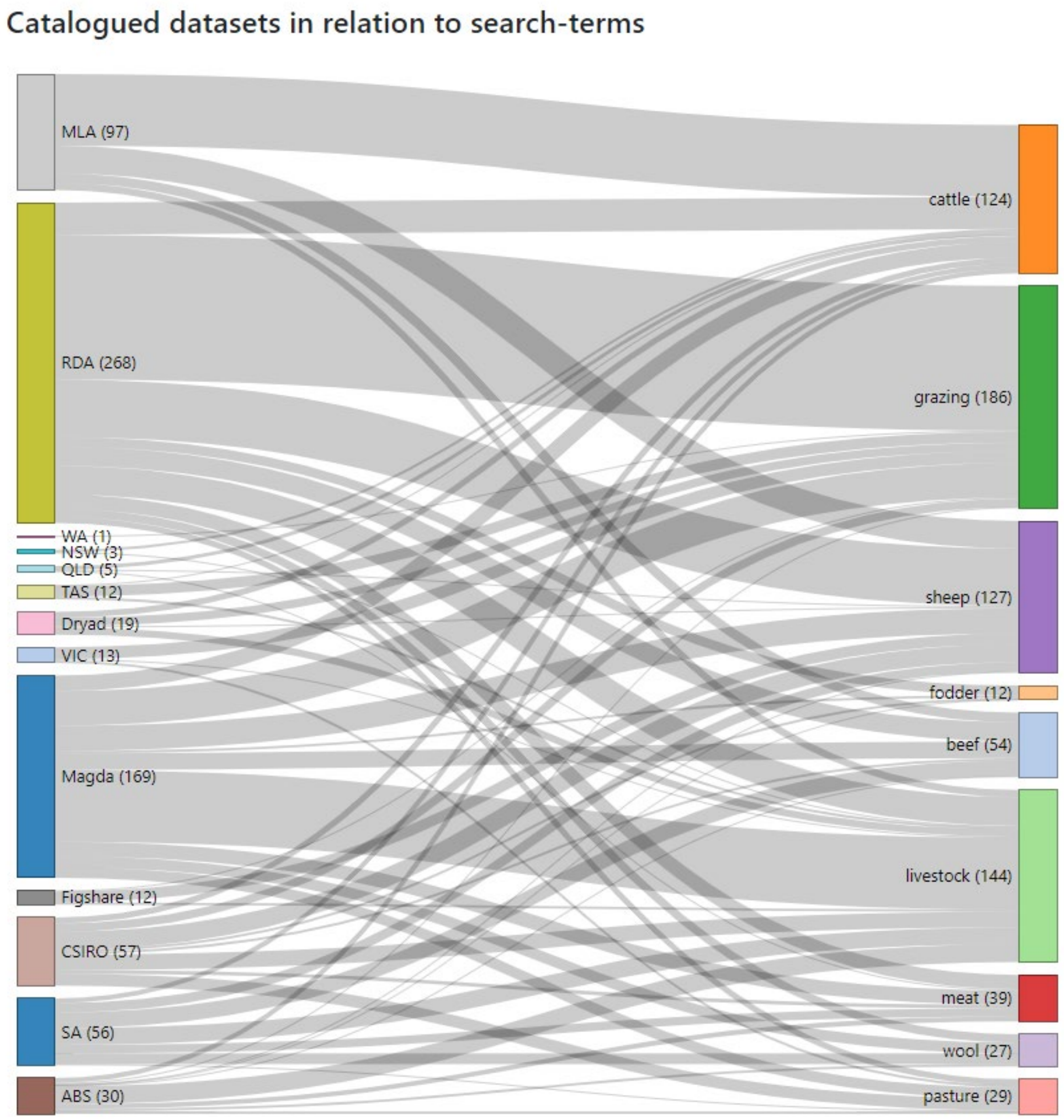

Figure 4.2 - Search terms in catalogues

4.1.3.6.2 Duplicates across catalogues

Further duplicates were a result of datasets being listed in two or more different catalogues. A graph showing the duplicates between catalogues is shown in Figure 4.3.

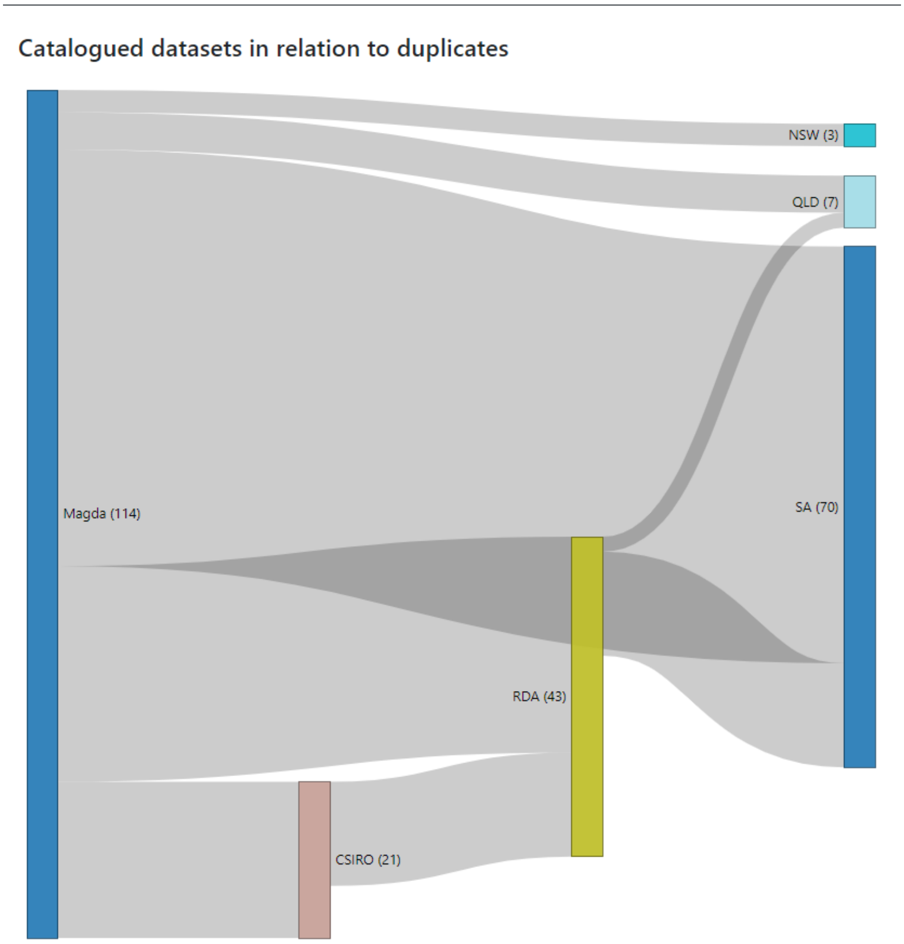

Figure 4.3 - Duplicates across catalogues

The removal of duplicates yielded the final table of 419 unique datasets for further analysis. This raw result set, as well as the scripts developed to query public catalogue APIs, other supporting files, documentation and an interactive view of the graphs can be found at http://doi.org/10.5281/zenodo.4057869.

4.1.3.7 Assess data quality

Two key questions of this systematic data review in relation to data quality are:

- How findable, accessible, interoperable and reusable are datasets within the livestock farming domain in Australia?
- How can the FAIRness of these datasets be measured?

Multiple methodologies have been developed to assist in assessing FAIRness, some of which have online tools or even facilitate automation. The methodologies were compared using the FAIR Data Maturity Model WG (2019) and the Data Ratings document by Yu and Cox (2018) to understand similarities and differences. Variations exist in how the FAIR principles are defined and assessed. A recent report published by the Research Data Alliance (RDA) identifies and analyses no less than twelve approaches to measuring FAIRness (FAIR Data Maturity Model WG, 2019). Some of these frameworks offer a questionnaire style of assessment that asks specific questions about the different aspects of FAIR. This includes two Australian frameworks, namely: The Australian Commonwealth Scientific and Industrial Research Organisation/OzNome 5-star System (Yu, 2017) (http://oznome.csiro. au/5star/) and the Australian Research Data Commons FAIR self-assessment tool[23]. The other assessment framework of interest is the FAIR Evaluation Services[24], which consists of modular FAIRness Maturity Indicators. This framework seeks to automate the assessment of specific FAIR characteristics of datasets and other digital objects and is intended as a tool to increase the FAIRness of resources, as feedback is provided by the software on why tests for specific FAIR metrics fail (Wilkinson et al., 2019). These tests can be run in the web portal or by using the FAIR Evaluation Services API, which required the development of a PHP script. A collection of 18 metrics tests was set up within the FAIR Evaluation Services portal [25], and the identifier of this collection together with the URLs of the datasets to be assessed were passed by the custom FAIR evaluation script (Bahlo, 2020) to the API.

[23] https://www. ands-nectar-rds.org.au/fair-tool
[24] https://fairsharing.github.io/FAIR-Evaluator-FrontEnd/#!/
[25] https://fairsharing.github.io/FAIR-Evaluator-FrontEnd/#!/collections/15

4.1.3.8 Results analysis

The results from the FAIR assessment and additional metadata analysis are presented below. The FAIR metrics tests used in the assessment are described in detail in Appendix 1.

4.1.3.8.1 FAIR assessment results

Each test was run on every dataset, with a success or failure outcome indicated in the response. 419 datasets were tested, with five returning no data (the assessment failed for reasons unknown). Figure 4.4 shows the numbers successful and failed tests for each of the 18 FAIR metrics applied for the remaining 414 datasets.

Figure 4.4 - FAIR tests with passes and failures

Five tests for persistence of identifiers and metadata identifiers were failed by all datasets. This is surprising as the identifiers used are all valid URLs. However, the tests look for specific types of identifiers, and if the parsing tools used within each test are unable to find one of the specific identifiers, the test fails. Only eleven datasets were findable via search engine (the test only uses the search engine Bing), which disagrees with a search using the

Google search engine that yielded many more results. Open data licences were found only in 21 out of the 414 datasets. The latter was surprising as the catalogue search results indicated a larger number of Creative Commons (CC) licenses.

4.1.3.8.2 Data licenses

Data usage license information is related to reusability. The FAIR assessment via the FAIR evaluator did not find all licensing information within metadata. However, the dataset search identified licences for all but 19 of the total datasets found.

Using the final list of unique datasets, the licenses were grouped and counted. All datasets having CC licenses (Creative Commons) were grouped by version, but without regard for special endorsements. CSIRO data licenses were shown separately. Every licence not recognised as CC or CSIRO license was grouped as “other” and datasets with no license information are listed as “unknown”. Figure 4.5 shows the percentages of licences across the datasets found in the search. CC licenses apply to 183 (44% of the total), which would indicate reusability and should have passed the R1.1 FAIR test.

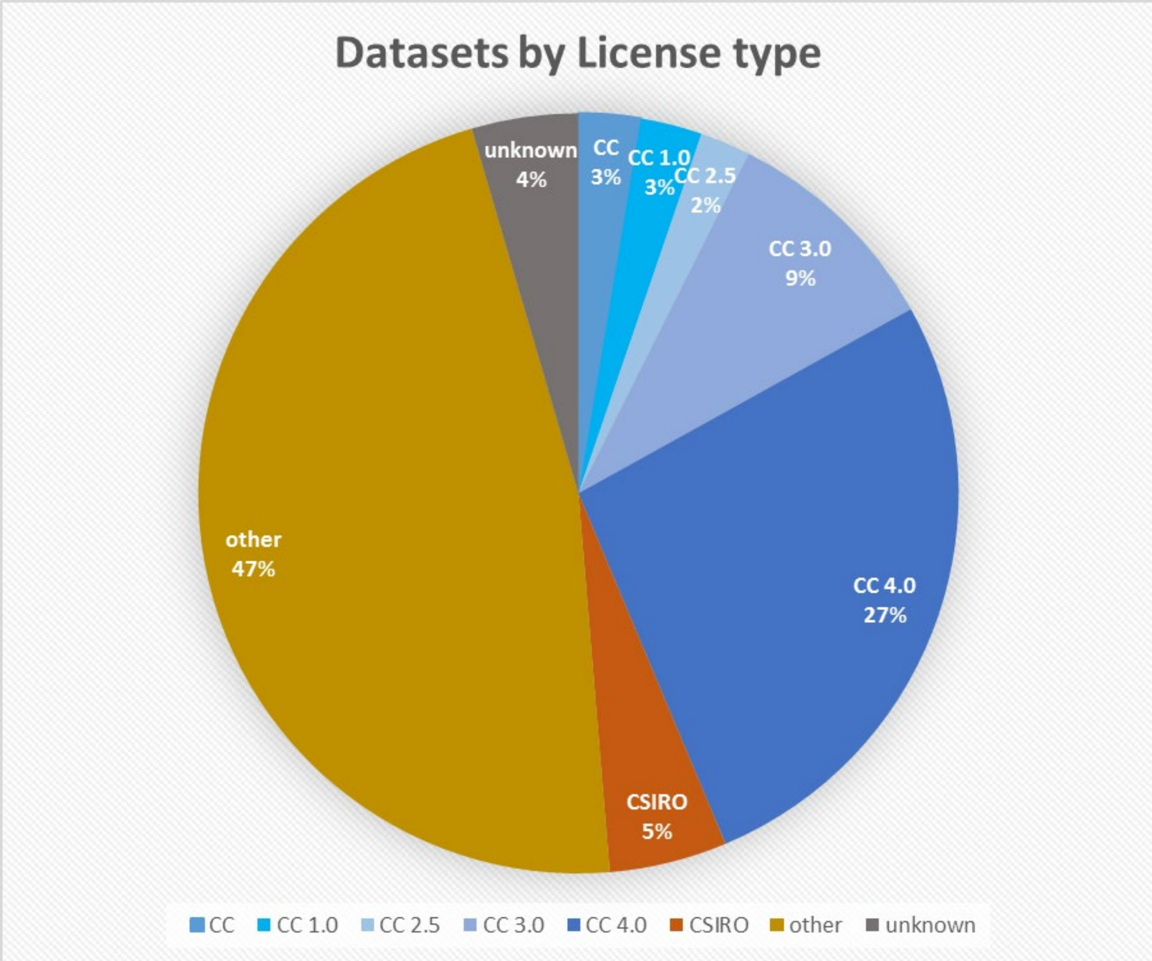

Figure 4.5 - Datasets by license type

The distribution of licences across catalogues is also relevant. This relationship between catalogues and licenses is shown in Figure 4.6. It is noteworthy that all licences other than CC licences were found within the RDA and MLA catalogues, whereas most of the other catalogues had various versions of CC licenses.

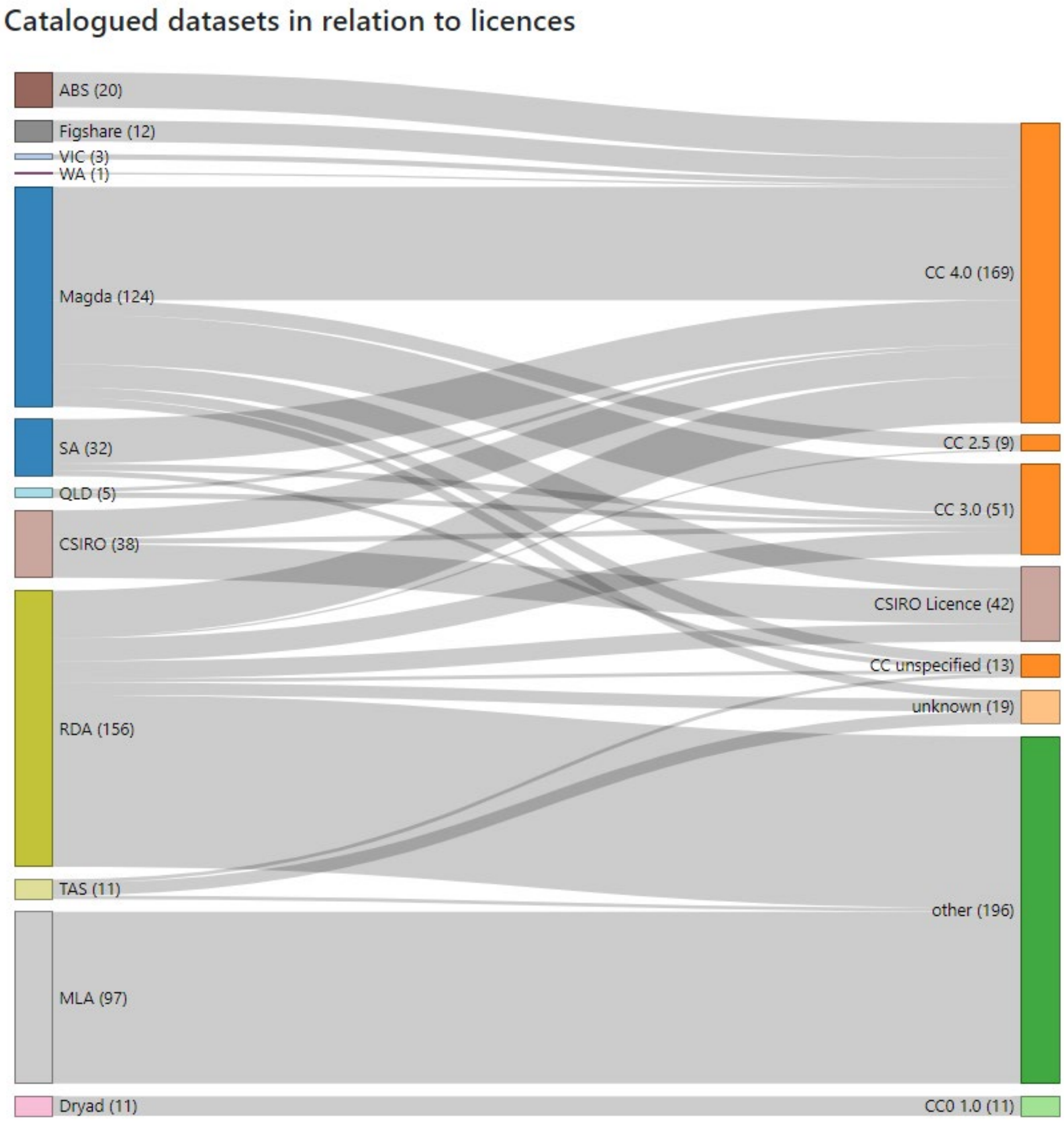

Figure 4.6 - Data licences in catalogues

4.1.3.8.3 Distributions

Most public datasets are available in multiple formats (referred to as distributions in some catalogues), where a format can be a file type, a web service or output from an API, such as JSON or XML. Most data catalogues list all available distributions for every dataset, but some catalogues do not provide this information. For the analysis, all distributions were grouped together by type, and all datasets were grouped by catalogue, and a relationship is shown for every distribution for every dataset. Figure 4.7 graphically illustrates the relationships between catalogues and all available distributions. The interactive graph for this and the above figures can be found at https://narrawin.github.io/datasearch/visualise/. The reason for the large number of unknown formats for the RDA catalogue is that the API queried for this search did not return metadata related to formats.

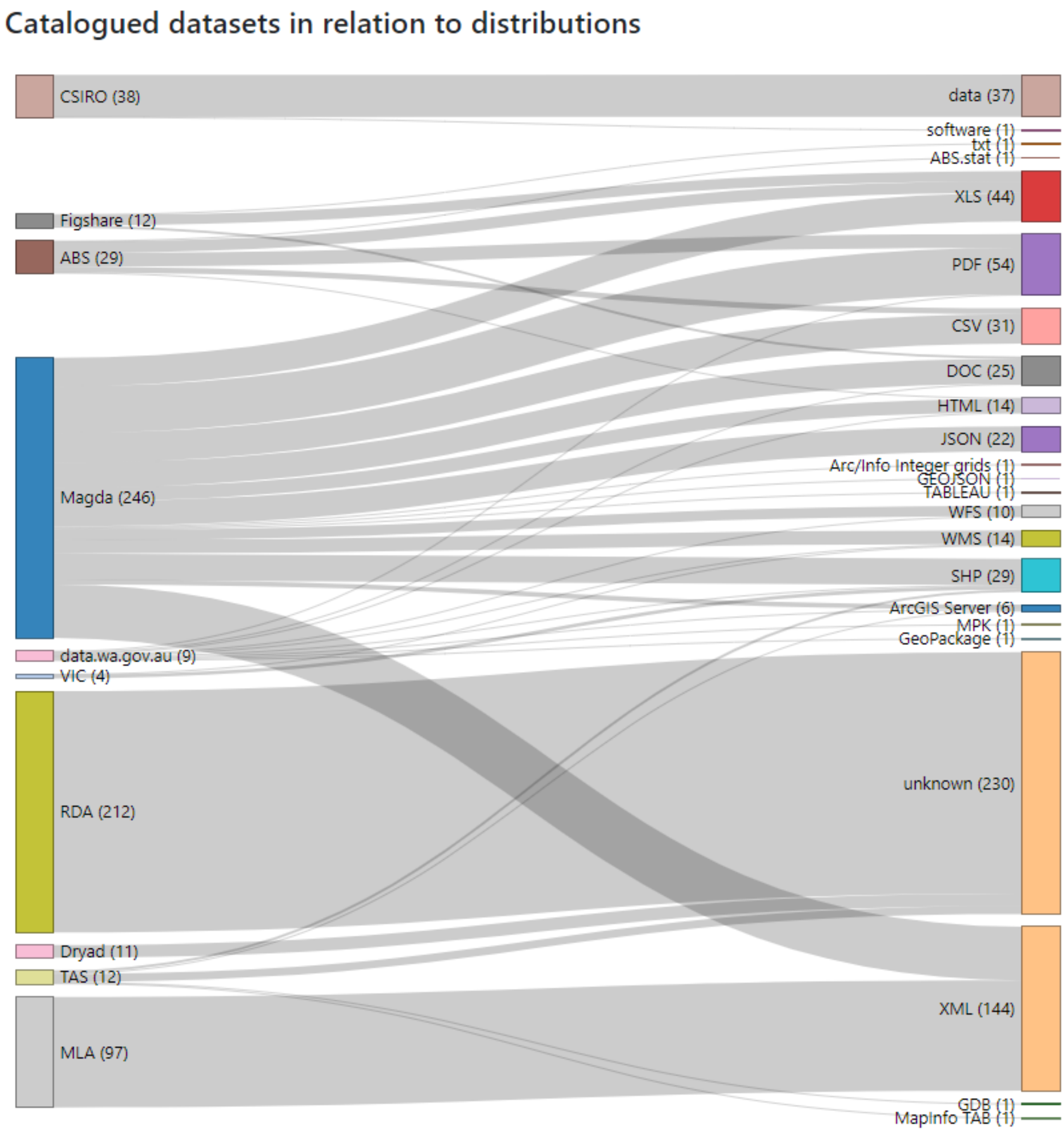

Figure 4.7 - Distributions

While this graph shows all available distributions, a test for FAIRness should consider only the most "open" distribution. For example, if a dataset is available via OpenAPI and in XLS format, the more open distribution is OpenAPI. Therefore, another useful way of looking at distributions is to only consider the best, that is, the most open distribution. Taking all 419 datasets, the best distributions by percentage unfortunately still shows 40% as unknown, but the open formats XLS and JSON together make up 39%. Web services such as the Open Geospatial Consortium's (OGC's) Web Mapping Service (WMS) and associated Web Feature Service (WFS) (which for the purposes of this analysis were grouped under WMS, because they were found to be provided together) were only present in a small number of datasets.

It is noted that data catalogues list services and non-data formats (e.g. PDF, DOCX) alongside data formats in metadata fields named "format" or "distribution", so they are not distinguished within the metadata records. Data can often be extracted from non-data formats, and interfaces are designed to provide data, and as data providers are agnostic of the purpose for which data may be used, this appears to be a reasonable approach. Unknown data formats are where the data format could not be obtained via an API, or the data type was described in the metadata as "unknown", so the high percentage is due to limitations in the API and to missing metadata.

Figure 4.8 shows the numbers of the best available distributions for the total number of datasets found.

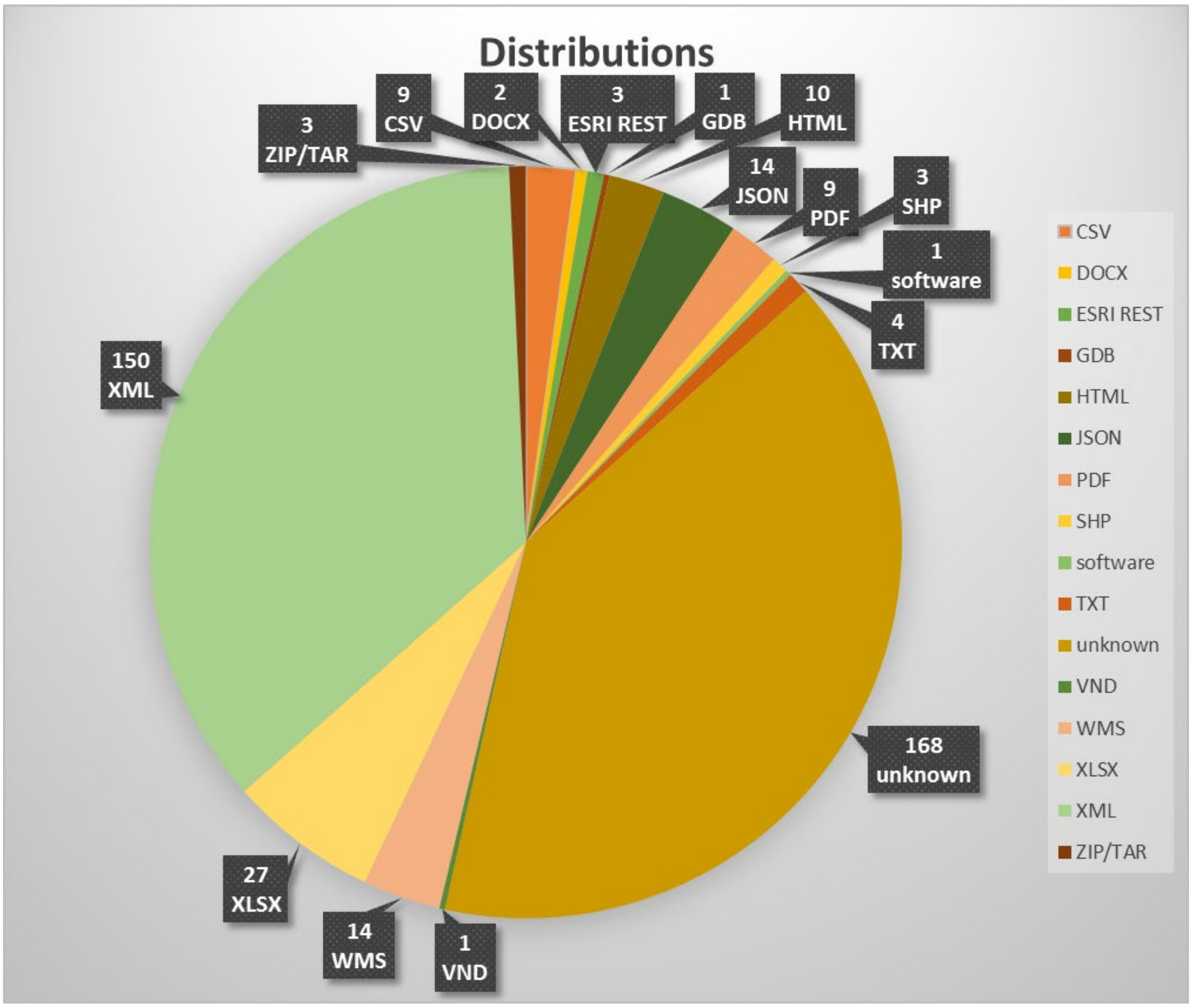

Figure 4.8 - Best distributions

4.1.4 Discussion

The process of finding datasets required some domain knowledge, both in terms of locating candidate catalogues and in determining what to search for within the catalogues. After identifying catalogues, each one was checked for retrieval capabilities. Accessible APIs for many of the data catalogues enabled efficient retrieval of search results, and ability to format the result set in a way that was conducive for comparison and analysis of datasets. The development of automated scripts facilitated rapid and mostly automated processes of gathering metadata, with the additional benefit of being reusable to locate datasets for future catalogue searches. The metadata for datasets was found to vary between catalogues, as was the way in which metadata is stored. There was also lack of consistency of naming of keys and metadata structure within the output from a single query of the catalogue APIs, which required some additional logic within the scripts that harvest the result. It would be possible to develop the scripts further to add new catalogues, retrieve additional information and have a better user interface, however even in their current relatively simplistic form, they show that harvesting metadata across different catalogues can be achieved efficiently.

On the other hand, a lack of public API access means that the search process for datasets and the obtaining of metadata is a manual process, which is more time-consuming and prevents any automation of data and metadata harvesting. In view of the current situation of only some data catalogues having public facing APIs, it is not possible to fully automate a dataset search across available open data catalogues. Therefore, this systematic review required manual searches as well as automated searches and the final result set of livestock industry public datasets combines information gathered in different ways. While every attempt was made to gather the same metadata about each dataset, the aforementioned differences yielded a result set that isn’t homogenous. In some cases, it was impossible to determine the type of data for a listed dataset, in other cases, no information about the licence was available. Also, identifiers were sometimes internal, and sometimes external. Differences in the use of identifiers caused some issues in determining where a dataset is listed in several catalogues. This was mostly resolved in one of two ways: the harvesting scripts used some logic to compare partial strings on identifier fields and the final combined spreadsheet ran a formula to identify duplicates by dataset name. However, it was still necessary to manually check and resolve some duplicates, as there were datasets of the same name but with different DOIs as well as datasets with different names, but the same identifier. Most of these issues could be resolved if all catalogues could be queried by scripts that handle all the comparison logic, or better still, one consolidated script to interrogate all available catalogues.

A FAIR assessment was undertaken, using the FAIR Evaluation Services API. As stated by Wilkinson et al. (2018), FAIRness is based on a number of aspects, and it is a spectrum rather than a true or false attribute of datasets. Therefore, each of the dimensions on FAIR, being findable, accessible, interoperable and reusable is split into subsets of testable qualities that need to be measured to determine the FAIRness of a dataset. A suite of 18 separate tests was selected for this purpose and all datasets found during the search were run though these tests. Some of the tests returned failures for all datasets (data and metadata persistence of unique identifiers) which appears to indicate a very low level of compliance with these relatively easy metadata requirements, or the tests check for conformance against a set of standards that may be too specific. This will require further investigation. Secondly, a very low level of compliance was found in two other facets (findable in search engine and license information), which did not agree with information obtained during the dataset search phase, and is thought to be related to lack of domain-specificity of the FAIR metrics tests applied.

4.1.5 Conclusions

The initial aim of this research was simply to undertake a systematic review of the available data related to extensive livestock farming in Australia, with a focus on the quantity and quality of datasets available. If the purported benefits of digital agriculture are to be realised, then this research represents a relevant test of bringing together big data as fuel for intelligent decision support systems. To achieve this aim, a method of systematically reviewing datasets was developed. The choice of measuring data quality in terms of FAIRness was underpinned by the desire to make an objective assessment through a framework that is emerging to be widely accepted across many domains.

Much of the work of this study addressed the findability of datasets, taking a systematic approach to finding catalogues, and within these, datasets. It is encouraging to find in excess of 400 unique datasets for a domain as specific as extensive livestock farming in just one country, excluding any datasets that would also be relevant, for example transport, weather, climate, soils or others. On the other hand, the spread of these datasets across multiple catalogues with different data and metadata characteristics and search facilities make finding relevant datasets a challenge. A more standardised approach to public data (Janssen et al., 2016) would facilitate two outcomes: firstly, the finding of unique datasets, and secondly the automated retrieval across all catalogues. These outcomes are highly desirable as early as possible as the livestock industry is transitioning towards a greater adoption of precision livestock technologies, as they facilitate the federation of public and private data to support decision tools (Yost et al., 2018).

Further work needed is the selection of an appropriate FAIR assessment metrics. Dumontier and Wesley (2018) note that FAIRness is based on the expectations of the stakeholder community and Wilkinson et al. (2019) go a step further by stating that FAIR metrics should be domain dependent and informed by domain experts. So, while FAIR principles are overarching and some aspects are generally applicable, some metrics should be determined by the domain within which a digital resource is situated. At the current time, no specific FAIR metrics or assessment methods could be found for livestock farming digital resources, or even for the broader domain of agriculture, so this study used a generic metric. The low scores in several of the tests across all the datasets tested may be affected by this lack of domain specificity, however the tests also identified areas where the adoption of FAIR principles is progressing well. We argue that the development of specific metrics or collections of metrics for FAIR agricultural data should go hand in hand with the development of FAIR data policies such as the Agricultural Research Federation (AgReFed)[26], which identify minimum standards of FAIRness in the agricultural domain (Levett et al., 2019). The lessons learned about sharing data by the geoscience community could be a valuable guide in the journey to greater FAIRness (Stall et al., 2019).

While further research and development is needed to advance the catalogue query scripts and to integrate them into a software application that provides decision support for extensive livestock farming, the methods developed by this research provide a foundation to undertake a systematic data review in any discipline.

4.2 Epilogue

This chapter answered questions related to the number and quality of public datasets for the extensive livestock farming domain. The search excluded related information such as weather, climate or soil data, as they are not specific to livestock farming. Also, due to their importance, they merit a systematic review in their own right. Indeed, using the software scripts developed in Chapter 5, I led the systematic review of soil datasets that was undertaken as part of another (as yet unpublished) study, which yielded 1760 Australian datasets. Soil and weather sciences are domains with long traditions of data collection, whereas livestock sciences appear to lack maturity in terms of data collection, storage and public availability. Therefore, it was encouraging to see over 400 public livestock datasets

[26] https://www.agrefed.org.au/

(within the chosen search parameters). It is expected that searches for specific terminology such as diseases, parasites, livestock classes and breeds will yield further datasets. Nonetheless, the findings of the dataset search indicate that more than expected public data is available for decision support tools and the development of the methodology and tools will be useful for future dataset searches regardless of domain.

A well-known Australian advertisement used the punchline that "oils ain't oils!" and likewise it could be said that "datasets ain't datasets!", meaning that not all datasets are of equal quality. FAIRness is one of the data quality "yardsticks" that can be used to measure dataset quality, by determining findability, accessibility, interoperability and reusability aspects of data and metadata. The systematic review used a set of FAIR metrics as quality assessment. Several FAIR assessment tools are available, but it was beyond the scope of the dataset search to investigate which of these tools (if any) would be best suitable for the task. The literature related to FAIR assessments is relatively sparse, and indicated that differences exist, but was not helpful in determining the best tool for this task. A secondary consideration was ease of use and speed of testing, therefore the tool that allowed automation of the FAIR assessment was chosen for the systematic review. A script was developed to access the FAIR assessment API, which allowed the processing of all datasets within a reasonable time. However, the outcome of the FAIR assessment indicates that a more nuanced approach should be taken in similar assessment in future, at the very least that should include a set of domain specific metrics rather than a default set. The results in relation to findability using a search engine (F4) need to be reviewed as only one Internet search engine was queried. Additionally, the inherent limitations of finding datasets mean that the search did not find all relevant livestock datasets, and more targeted searches may be necessary to locate these.

The analysis of the datasets did not include other characteristics, for example the spatial and temporal extent. This was out of scope, and it is noted that the available metadata did not always provide this information. Additional studies would be needed to determine these characteristics within Australian livestock datasets.

Lastly, the quality assessment does not in itself give an indication about the usefulness or fitness for task for a given dataset for a given livestock decision tool, be it a geospatial portal or another application. Usefulness depends on the use case and on data parameters, for example data currency, temporal resolution of observations and spatial resolution. Usefulness of public data for a specific use case will be investigated in the next chapter.

5 Can we answer livestock welfare questions with public data? A case study from Australia

Among the conclusions in the literature review is the recommendation to build a geospatial portal to bring together interoperable data sources to assist decision support for precision livestock farming. This concept was explored in a conceptual animal welfare and production application (Bahlo, 2017), which was presented at a precision livestock farming conference.

The systematic dataset review in Chapter 4 attempted to answer questions about quantity and quality of datasets specific to extensive livestock farming, with an emphasis on FAIRness of data. The search results included a set of potentially useful datasets for farm animal welfare, and the techniques and software scripts developed during this review provide a starting point for further searches of datasets within this case study.

The purpose of the systematic dataset review was to test the breadth and quality overall of datasets for the domain, but still does not answer the question whether public data is adequate to support PLF or provide decision ready information for extensive farming systems in its own right. To answer this question, a case study is used to document public data availability and usefulness for one specific topic in a limited geography.

5.1 Can we improve livestock welfare with public data? An Australian case study

5.1.1 Abstract

The production of food and fibre from extensive livestock farming is an important industry in most countries but is under increasing scrutiny of its social licence to operate. While the concerns are wide-ranging, this chapter examines the potential to inform the debate by integrating information using publicly available open data sets. Taking the use-case of beef-

cattle farming in Australia, we test whether the evidential base for animal welfare outcomes can be managed and verified, without using traditional Precision Livestock Farming methods, such as on-farm sensors, on-animal sensors and direct measurements. Using 54 publicly available open data sets sourced from 23 catalogues, we demonstrate that animal welfare hazards can be mapped. However, due to the interdependency of animal welfare hazards and their variable urgency with time and place, the limitations of data resolution, and spatial and temporal coverage, will need to improve before the welfare maps can used with confidence. Despite these limitations, the research clearly demonstrates the ability to provide the evidence for several of the critical issues in the social licence to operate, including legitimacy, trust, transparency and communication.

5.1.2 Introduction

Food security for a global population of almost 10 billion people by 2050 (United Nations Department of Economic and Social Affairs Population Division, 2019) will require improvements in the quantity and efficiency of food production, which is subject to many challenges (Stephens et al., 2018). Agriculture is forced to deal with pressures resulting from climate change (Perarnaud et al., 2005), loss of productive land from urbanisation and desertification (Fedoroff et al., 2010), pests (Fox et al., 2015) and diseases, increasing regulations and rising levels of scrutiny of its social license to operate.

Livestock farming in particular faces increased public scrutiny for environmental impacts and sustainability (Eisler et al., 2014), ethical and practical questions with respect to the relative cost of producing plant based human food versus animal based human food (Tichenor & Leach, 2017) and animal welfare (Fraser et al., 2013; Grandin, 2014). Adding to the complexity of livestock production, some of these facets are interdependent (Weindl et al., 2015), whereas others require trade-offs (Kanter et al., 2016).

Information technology is revolutionising agriculture (Cox, 2002) with precision farming technologies increasing production efficiencies. Precision Livestock Farming (PLF) technologies were first adopted in intensive livestock farming (Banhazi & Black, 2003) but remain less advanced in extensive and rangeland livestock farming systems, particularly in the development of modelling and the adoption of technologies (Kipling et al., 2016). While this seems surprising when considering the size of the global extensive livestock farming industry, technological limitations and the environment that grazing animals inhabit pose multiple challenges (Morris et al., 2011).

Rojo-Gimeno et al. (2019) looked at the cost and value of (more) precise information obtained with PLF, concluding that the cost mostly outweighed the value, even if that value included non-monetary benefits for farmers. However, PLF data could be used outside the entity that collected them and may be a valuable farm output (Ramirez et al., 2019). While current and historical data collected in the private sector is potentially a great information resource to the livestock industry as a whole, it is almost unused in anything other than small-scale software applications due to farmers' concerns regarding data privacy and security (Wiseman et al., 2019).

While the aim of PLF is to facilitate extraction of information from a wide variety of sources (Berckmans, 2014), it appears to mostly ignore the potential value of existing publicly available datasets that could, if suitable, be federated with on-farm PLF data to create greater value to individual livestock enterprises or the industry as a whole. The value in amalgamating private and public sector agricultural data has been described by Antle et al.

(2016a) and Yost et al. (2018), and requires making disparate data interoperable, to be understood by both the data supplier and consumer, including agricultural decision support systems (Janssen et al., 2016). Examples of successful data federation[27] of open and private data exist in related domains, such as soils (Robinson et al., 2019) and groundwater (Brodaric et al., 2018).

In relation to extensive livestock farming, the quality, availability and usefulness of existing public datasets has been questioned, especially their pragmatic application (Bahlo et al., 2019). Using the publicly available data from Australia, we attempt to answer those questions of practical value using an animal welfare case study, which is a topic of global importance for the extensive livestock farming industry.

Minimum animal welfare standards in livestock production systems are mandated in Australia as well as several other countries (Blandford & Harvey, 2014; Coleman, 2018) , increasingly requiring record-keeping of individual animal treatments. Transparency of animal welfare management is highly desirable from an ethical (Fraser, 1999), public perception (Coleman, 2018), production output (Hocquette et al., 2014; Morris et al., 2011), biosecurity, and consumer supply chain perspectives. PLF has potential to track farm animal welfare management in the livestock industry mainly by way of recording the health of individual animals, for example by linking electronic tags (Morris et al., 2011) with on-animal sensors and automated systems. However, rangeland and extensive livestock farming systems have numerous additional challenges to contend with (Petherick, 2006) (cf. intensive animal farming), raising the question whether sensors can be used effectively and efficiently to record animal welfare management in those settings (Fogarty et al., 2019). Of

[27] Using the definition of data federation provided in the glossary.

course, PLF is not limited to sensors and automation but encompasses a wide spectrum of technologies and data science. This use-case tests whether welfare outcomes can be managed and verified with information technology and public data without involving the use of sensors and direct measurements by attempting to map animal welfare hazards.

5.1.3 Methods and results

This case study has three components:

1. Welfare elements. The identification of animal welfare elements related to environmental factors and translation of the elements into searchable terms
2. Data search. The identification and search of public open data catalogues and other sources
3. Data analysis. The spatial visualisation of the search outputs and analysis of results to determine their practical usefulness as a measure of animal welfare

5.1.3.1 Welfare elements

The scope of the case-study is limited to cattle and refers to the Australian Animal Welfare Standards and Guidelines for Cattle (Animal Health Australia, 2014), and the list of welfare elements contained therein. From this list, the welfare elements related to environment and location were selected, disregarding any elements related to management and handling of animals, as well as those related to intensive enterprises such as dairy farming, feedlots and calf raising. The selected welfare elements were consolidated and grouped into the following list:

- Weather
- Feed availability

- Water availability
- Diseases
- Parasites
- Deficiencies
- Toxins
- Veterinarian
- Breed suitability
- Natural disasters
- Predators

For each welfare element, suitable words were determined to search public catalogues for available datasets (Table 5.3). For diseases, deficiencies and parasites, additional information was sourced in online government and industry body publications. A full list of sources related to specific welfare elements is included in the supplementary material.

Table 5.3 - Welfare elements

Welfare Element	Search terms
Weather	Rainfall, wind, temperature, storm, frost Climate zone
Feed availability	Available pasture Pasture growth Feed on offer Travelling stock reserve (TSR), stock route network (SRN)
Water availability	Surface water, groundwater
Diseases and infestations	17 common cattle diseases 12 other diseases, infections, infestations of cattle 6 notifiable diseases that are found in Australia

Welfare Element	Search terms
Parasites	15 cattle parasites as specified in The cattle parasite atlas (MLA, 2005)
Deficiencies	Copper deficiency Selenium deficiency Cobalt deficiency Phosphorous deficiency
Toxins	Environmental toxin (soil, air, water) Plants toxic to cattle: Pimelea, Death camas, Nightshade, Poison hemlock, Water hemlock, Larkspur, Paterson's curse, Perennial ryegrass, St John's wort Snake envenomation
Veterinarian	Veterinary practice, veterinarian
Breed suitability	Specific characteristics: heat tolerance, cold tolerance, disease resistance
Natural disasters	Bushfire, flood, earthquake, storm
Predators	Wild dogs, feral dogs, dingos

Relationships exist between welfare elements, indicators of good welfare, and soil. While not investigated specifically, datasets may provide information for more than one welfare element, based on these relationships, which are shown in Figure 5.9.

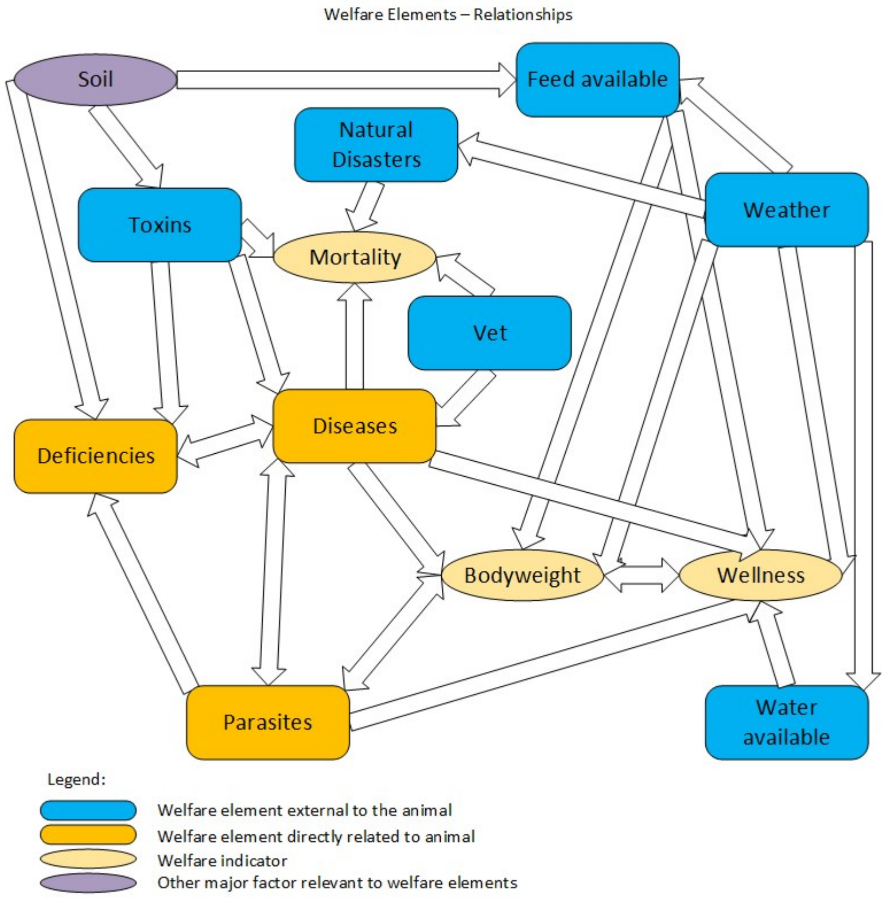

Figure 5.9 – Welfare Elements – Relationships

Due to the close relationship between diseases, deficiencies and parasites, overlaps exist in the literature and in the datasets found, so these three welfare elements were treated as one during the data search.

5.1.3.2 Data search

The dataset search was conducted on 24 repositories, which included 14 government catalogues, eight research institutions, one industry body and Google Dataset Search. A full listing is included in the supplementary files.

Data search tools developed for a previous study were used (Bahlo, 2020), as well as manual searches of data catalogues and Google searches. The results were summarised and checked for data type, licence, spatial resolution and other quality parameters to determine suitability for this study. Temporal or spatial qualifiers were not set during the data search. Brief detail for each welfare element is presented below.

5.1.3.2.1 Weather

Temperature extremes and humidity, storms, heavy rain, hail or snow can affect the welfare of grazing animals. While grazing animals can tolerate range of temperatures and some inclement weather, the further environmental temperatures deviate from the ideal, the greater the chance that welfare and production will suffer (Herbut et al., 2018). Studies with dairy cattle indicate that the two main environmental risk factors are air temperature and relative humidity (Herbut et al., 2018).

The most relevant dataset source, the Australian Bureau of Meteorology (BOM), publishes a number of useful datasets for climate zones, including temperature and rainfall zones, frost days, drought areas, and other aspects, although the resolutions vary from national scale to individual states or territories. A search of other data catalogues yielded two datasets from the State of Queensland's Qspatial catalogue which track the frequency of cyclonic wind gusts.

5.1.3.2.2 Feed availability

In a grazing system, feed availability is related to soil type, slope, aspect and other landscape factors, but also rainfall, temperature, pasture type, existence of other plants and grazing pressure. Feed on offer in a pasture can be estimated by sensors or based on models. Spaceborne, airborne or ground sensing acquires imagery and calculates quality through normalized difference vegetation index (NDVI) and quantity through Light Detection and Ranging (LiDAR) (Schaefer & Lamb, 2016). Feed availability can also be calculated, using Land Use Capability (LUC) classification systems and simulations that take into consideration rainfall, soil types and other land characteristics (Holzworth et al., 2014; Vogeler et al., 2016).

Two relevant datasets were found on the BOM website, one for monthly NDVI[28] and one that models daily root zone soil moisture[29], which is critical for pasture growth. Open access Pastures from Space datasets for Western Australia can only be viewed via a web portal, and the remaining tools are commercial pay-to-access arrangements. Sentinel satellite imagery is available at 12 hourly intervals, however it requires additional calculations to obtain NDVI and Biomass information.

Additional sources of pasture for livestock can be found in a network of routes and reserves across Australia. Queensland's stock route network and New South Wales' travelling stock reserves are available for download in disparate but usable formats.

5.1.3.2.3 Water availability

The availability of good quality drinking water is essential to livestock welfare. Water supply can be sourced from surface water: dams, creeks or rain stored in tanks, or from groundwater via bores. Hydrological landscape features can be useful to determine water availability and are available from BOM via the Geofabric Open Geospatial Consortium (OGC) Web Services[30] and the Australian Groundwater Explorer. Datasets are also available from the Visualising Victoria's Groundwater portal[31] and the CKAN catalogue of the Centre for eResearch and Digital Innovation (CeRDI)[32].

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[28] http://www.bom.gov.au/jsp/awap/ndvi/index.jsp
[29] http://www.bom.gov.au/water/landscape/
[30] http://geofabric.bom.gov.au/documentation/
[31] https://www.vvg.org.au/
[32] http://data2.cerdi.edu.au/dataset?tags=VVG

A search for farm dams using the search tools yielded two state level datasets for Victoria and New South Wales. A Western Australian dataset is listed but only available as metadata, so it could not be used. In addition, Geoscience Australia (GA) provides statewide and nationwide datasets of surface hydrology via ArcGIS MapServer.

5.1.3.2.4 Conditions affecting cattle: Deficiencies, parasites and diseases

Reid and Horvath (1980) investigated the relationship between soils and mineral deficiencies and the resulting health problems in ruminant grazing animals. The main deficiencies in cattle are copper, selenium, cobalt and phosphorous, which guided the dataset search.

A search for soils deficient in phosphorous yielded one dataset for New South Wales and Australia-wide maps of soil phosphorous prepared by Viscarra Rossel and Bui (2016) were obtained via the CSIRO Data Access Portal. A report published by Meat & Livestock Australia cites a national map of copper deficiencies (Dickson, 2016) and Hayes et al. (2019) developed a similar map by combining data from several studies, but neither are publicly available in a spatial data format.

The Cattle Parasite Atlas references internal and external parasites of cattle, (Meat & Livestock Australia, 2005), but associated datasets could not be found. Many parasites and diseases are enzootic – their occurrence and spread are determined by geography or climate zones and can fluctuate seasonally. Gastrointestinal parasites are widespread in Australia; some species are more prevalent in winter rain climate zones while others prefer a warm and humid climate, which is also the preferred habitat of biting and sucking flies. Liver fluke is endemic, except in fluke-free Western Australia, and both liver and stomach flukes require snail species and wet areas to complete all stages of their lifecycle. Maps with approximate distributions of flukes, worms and flies were found in several publications as images, but geospatial datasets could not be located.

Australia is home to 70 tick species (Barker et al., 2014). The main cause of economic losses to the cattle industry are caused by Australian cattle ticks (*Rhipicephalus*) (Jonsson, 2006), while Paralysis ticks and Bush ticks impact cattle to a lesser degree. Tick-borne diseases of cattle cause irritation, anaemia and death, and occur in climatic regions with high humidity and warmth (Animal Health Australia, 2018). Movement of tick-infested cattle is limited by designated cattle tick zones and cattle tick clearing facilities, which are available as downloadable datasets. Occurrence records were searched in the Atlas of Living Australia (ALA), which was successful for paralysis ticks and bush ticks, but not Australian cattle ticks. Other maps showing distributions of several tick species that affect animals and humans (Barker and Walker (2014)) are not available as geospatial datasets.

A total of 83 cattle diseases were investigated. Of these, 54 were excluded as they are not present or not observed in cattle in Australia, or because they are present in all parts of the continent, but not mapped. The remaining 29 conditions that were limited to specific geographies were included in the dataset search.

The search yielded only one usable dataset for the Bluetongue Virus Zone from the National Arbovirus Monitoring Program (Animal Health Australia, 2020). Multiple references were found in the published and unpublished literature regarding disease distributions, including illustrative maps, however none were available in a digital spatial format. Evidence for the existence of datasets was found in relation to Anthrax, which occurs mainly within the "Anthrax belt" and distribution was investigated by Barro et al. (2016), but associated data is considered sensitive information by the Australian governments and therefore unavailable.

5.1.3.2.5 Toxins

Substances toxic to cattle can be found in the environment (air, soil, water), in feed or animals. Toxicity in feed occurs via plants accessible to grazing cattle (or via fodder introduced to a farm, which is outside the scope of this study).

A list of plants toxic to cattle was derived from sources tabulated in the supplementary material. Searches based on common names yielded no results in the data catalogues or though Google dataset search. However, occurrence records based on the scientific names were obtained from the ALA for nine of the toxic plant species, although two of these showed no occurrences within Australia.

Limited information about environmental toxins is available through Environmental Protection Agencies (EPA) in Australia such as contaminated sites[33] [34], but these rarely occur on grazed land.

Snakebite envenomation has high mortality rates in grazing animals, but the economic impact is unclear (Bolon et al., 2019) and a geographic link could not be established.

5.1.3.2.6 Veterinarians

The proximity of a veterinarian to the location of a livestock farm is desirable, both for routine and emergency procedures. None of the veterinary boards or equivalent bodies in

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[33] https://www.epa.vic.gov.au/for-community/environmental-information/waste/landfills/victorian-landfill-register

[34] https://www.epa.nsw.gov.au/your-environment/contaminated-land/notified-and-regulated-contaminated-land/list-of-notified-sites

States and Territories provide the required information and inadequate data prevented the creation of a map.

5.1.3.2.7 Breed suitability

The suitability of a breed of cattle for a given geography or climatic region is determined by genetic adaptation to the prevailing conditions, therefore a good match between genetics and the environment is a welfare issue (Fraser et al., 2013). *Bos indicus* breeds are better adapted to hot and humid climates than *Bos taurus* breeds (Jian et al., 2014), but age, physiological state and body condition also affect temperature tolerance (Van laer et al., 2014). A review of the literature related to breed suitability for given environmental conditions found many studies have been published on specific trait in beef and dairy cattle and recommendations of breeds for climate zones, but no datasets were found that link breeds to specific geographies or climatic regions in Australia.

5.1.3.2.8 Natural Disasters

Natural disasters in Australia include wildfires, floods, severe storms and earthquakes. Emergency warnings fall outside the scope of an animal welfare portal and flood, fire and other warnings are provided via each State's emergency warning systems and maps.

However, identification of areas prone to fires or flooding are relevant as they can be used in preparing plans to move cattle to safer places. A number of national, state level and more local flood or fire risk map portals exist, but data is rarely accessible. However, two national datasets related to flammability and fuel moisture content were found as well as bushfire prone land in New South Wales, cyclone frequency in Queensland and flood prone land in Western Australia and New South Wales. Unfortunately, flood risk datasets were not available for all of Australia.

5.1.3.2.9 Predators

Unlike sheep, cattle are generally not affected by predators in Australia, however dingos and wild dogs can injure or kill calves. A search found four disparate sources of data for various sections of the fence, of which three were usable.

Wild dog sighting data were found in an aggregated national dataset of vertebrate pest animals (Australian Bureau of Agricultural and Resource Economics, 2006). Unfortunately, this dataset is several years old and unlikely to be updated due to the effort required to gather data from a large variety of sources and merging it into a national dataset.

5.1.3.3 Data analysis and results

The datasets found in the search were tested in the open source geographic information system QGIS (QGIS.org, 2020). This step was principally a visual check and included eliminating datasets that displayed incorrectly or didn't contribute useful information.

The visualisation also tested how datasets from disparate sources can be shown together, for example occurrence records, disease zones and climate data. Some examples are illustrated in Figures 5.10 to 5.13.

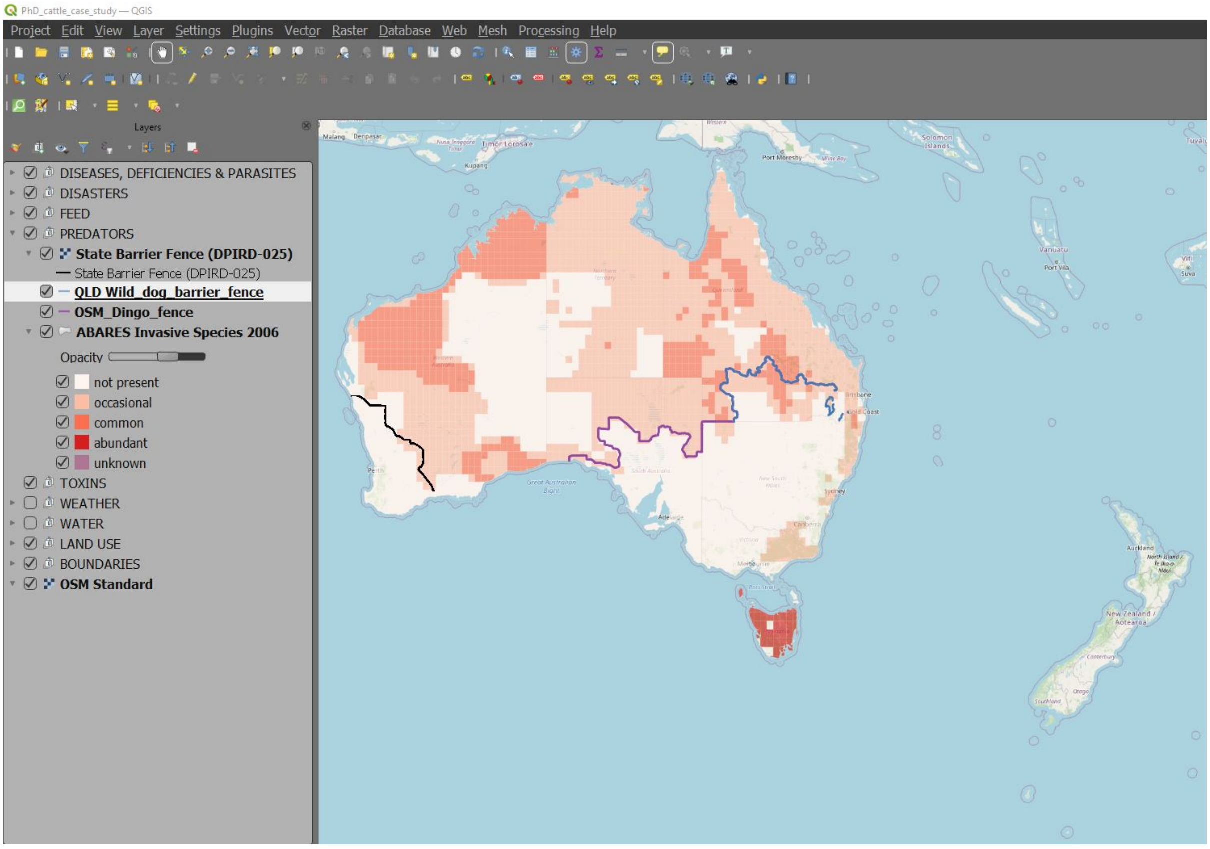

Figure 5.10 – A predator collage illustrating wild dog abundance and dog/dingo fences from four sources

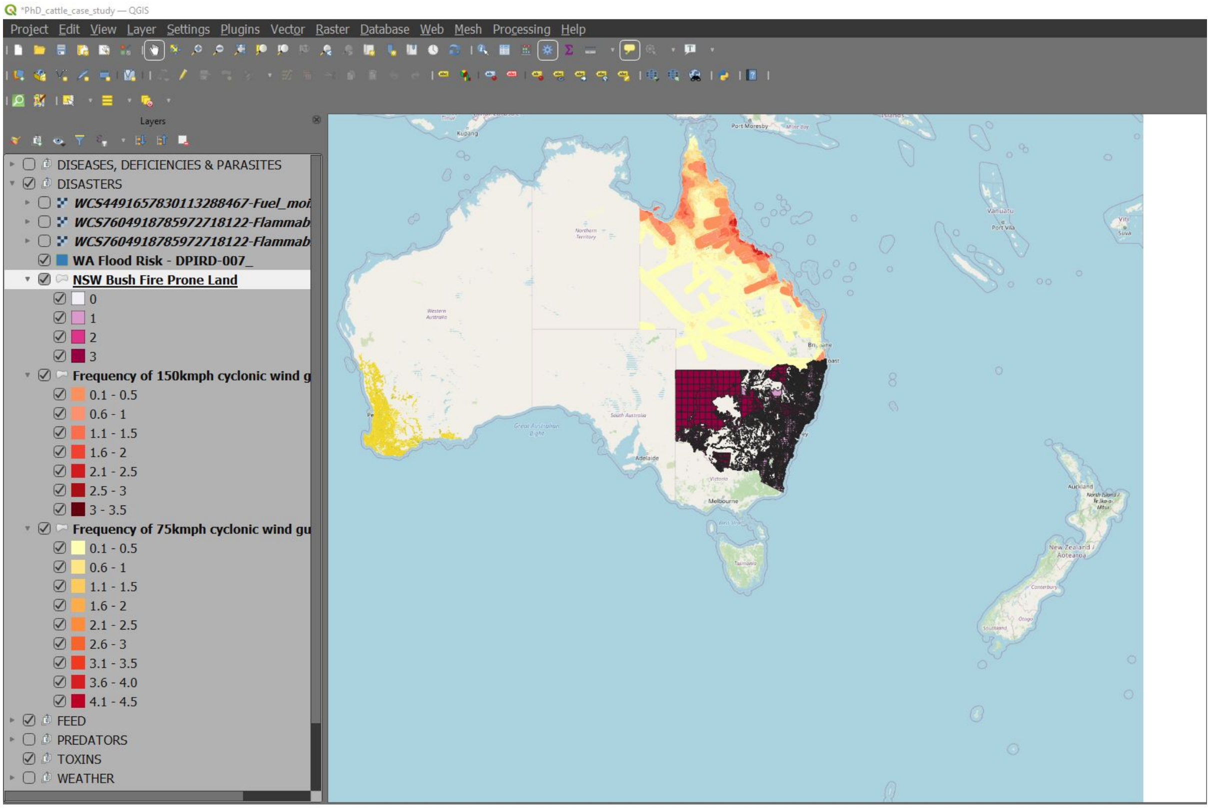

Figure 5.11 – A natural disaster collage showing Western Australian flood prone areas, New South Wales fire risk areas, and Queensland storm data

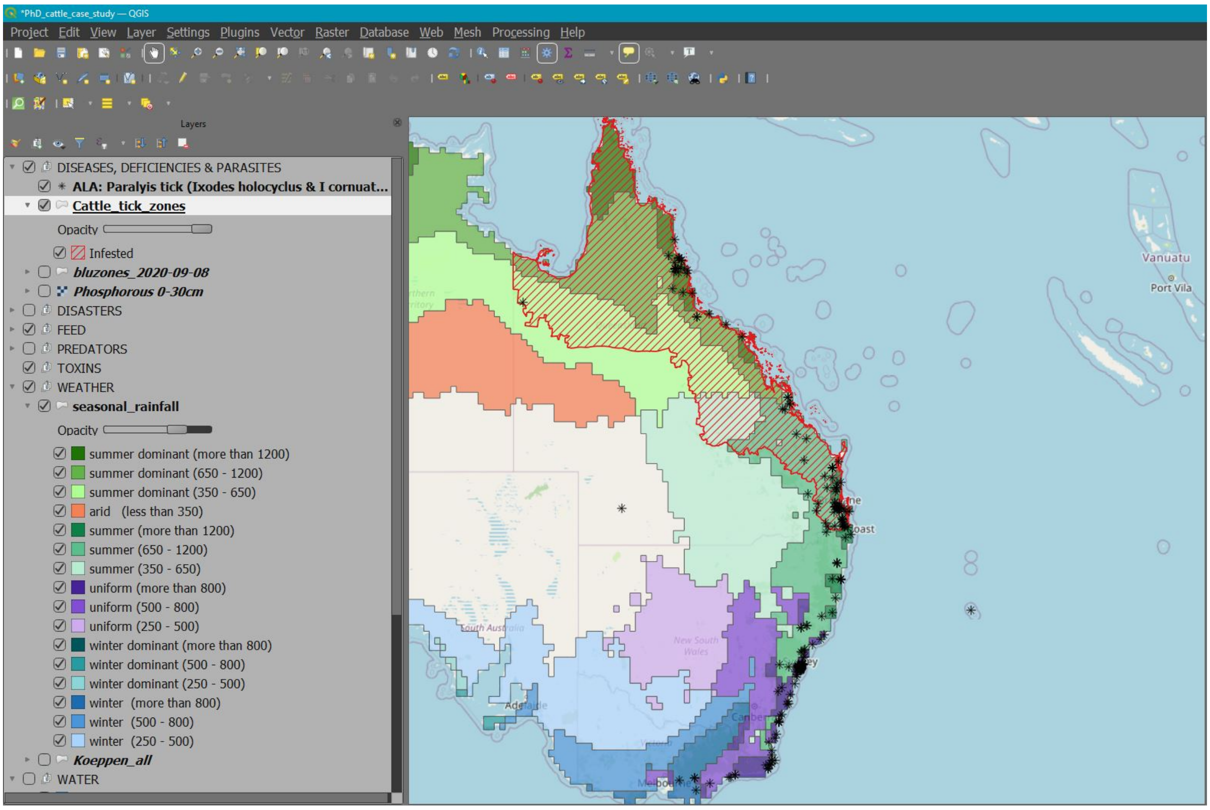

Figure 5.12 – A collage of weather and disease information showing national rainfall zones, Queensland tick zones and national paralysis tick observations

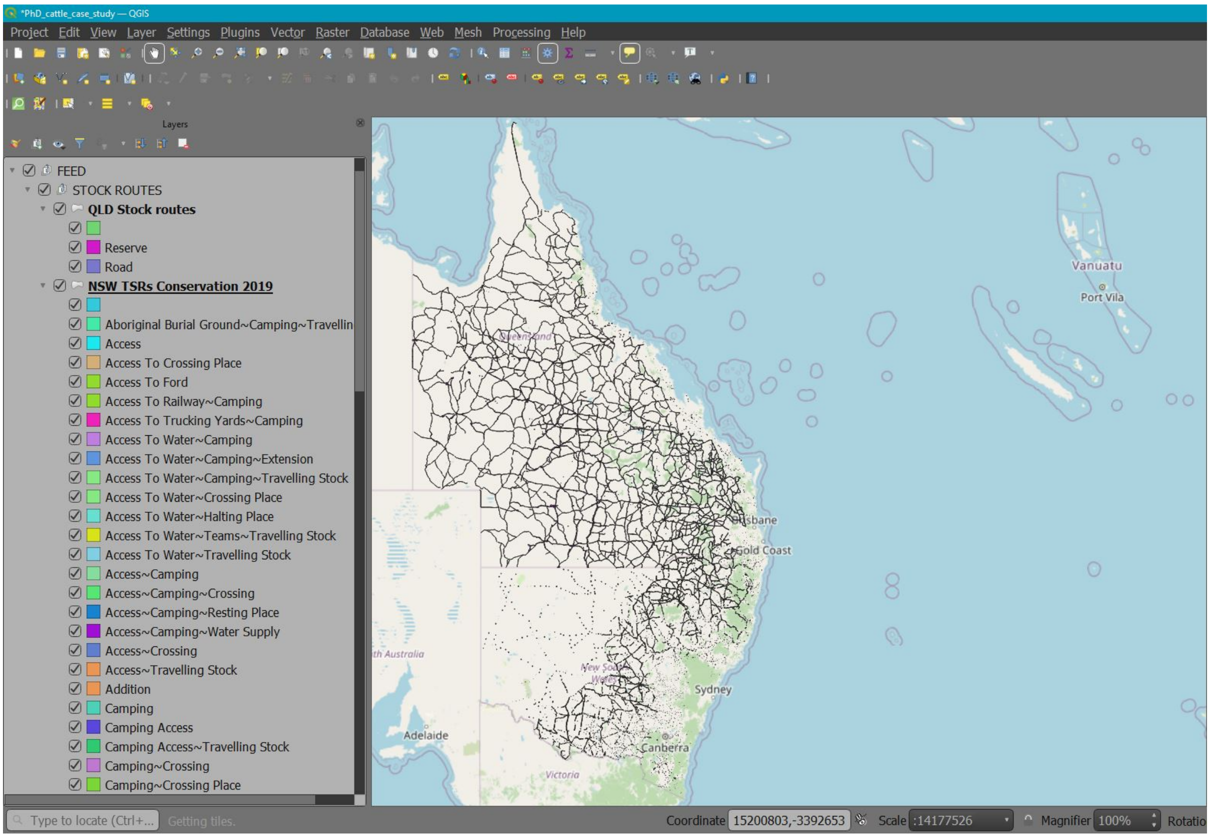

Figure 5.13 – Travelling stock reserves and stock routes for two states in eastern Australia

The ease of finding datasets varied from being listing in one or more of the Australian public data catalogues to requiring Internet searches for multiple similar words. Significant differences were also found in relation to data provisioning. The "best" datasets to include in a geospatial portal are those served as OGC standards-compliant web services, via a standardised interface from a database maintained by the custodian. The next best datasets are provided as Application Programming Interfaces (APIs) that are not OGC compliant but are still managed and updated by the data custodian. Less convenient are public datasets requiring a download of an open format file, for example ASCII text, JSON, XML or CSV, that contain spatial co-ordinates and can be added to a Geographic Information System (GIS).

Downloadable files in proprietary formats are less desirable, as are files that contain datasets that cannot be easily mapped into a GIS.

5.1.4 Discussion

Livestock is subject to welfare risks, and the need to assess and manage these risks is well recognised and subject to legislation in many countries. Risk depends on the likelihood of an event that compromises animal welfare and the consequences of such an event, therefore assessments include the identification and characterisation of hazards, exposure assessment and risk characterisation (Algers, 2009). A hazard has been defined as anything occurring during the animal's life that potentially causes detrimental animal welfare outcomes (Smulders, 2009). General farming practices, particularly in extensive animal farming are less regulated than intensive housing or specific aspects such as transport, procedures and drug administrations, and overarching risk frameworks for grazing animals could not be found.

The initial goal – a risk map of environmental welfare for grazing animals – is highly desirable to support welfare risk assessments, but there is insufficient available information to determine consequences without taking farm-level management into consideration. For example, there may be a high likelihood of parasitic infection, but the risk of negative welfare outcomes is mitigated by management strategies such as rotational grazing and chemical treatment of the animals. Likewise, likelihood is dependent not just on a long-term presence or absence of a potential welfare threat, but also on temporal changes to those threats. Most of the datasets found during the search lack the temporal resolution and necessary regular updates to facilitate this. Therefore, welfare risk mapping is not achievable using currently available open datasets.

However, while a risk map is not possible, this investigation has demonstrated the capability for a hazard assessment, taking hazard to mean “a source of potential harm” (International Organization for Standardization, 2018). By investigating the welfare elements contained in the Australian Welfare Standards and matching these to open datasets, a novel method of identification and mapping of environmental welfare hazards was demonstrated that has the potential to be a valuable source of information for on-farm risk assessments.

The results of the dataset search and analysis revealed opportunities and limitations. The primary limitations were lack of spatial and temporal coverage for current data (cf. legacy data):

- Datasets could not be found for two of the welfare elements.
- Age of datasets: wild dog abundance data is 14 years old, Queenland’s cattle tick zone dataset is from 2016, tropical cyclone data for Queensland is from 2014 and the travelling stock reserves information for New South Wales is from 2010
- No datasets could be found indicating the geographic distribution of cattle diseases, with the exception of one dataset related to the distribution of the Arbovirus causing Bluetongue, which is regularly updated. The literature mentioned several diseases and parasite infestations as having geographic and climate zone based distributions, but the underlying data was not available.
- Toxic plant occurrence records were obtained from ALA, but some of the observations included date back to the beginning of record keeping in Australia and are therefore of limited use in informing present day distributions.

Additional challenges were:

- Low spatial resolution of datasets. For example, national soil datasets were 90-100 metre grid cells and climate datasets were even coarser, varying from 2.5 to 5 kilometres, with some using 25-kilometre grids.
- The gridded climate datasets required clipping and transformation, and manual downloading from BOM at regular intervals.
- Occurrence records from ALA (for toxic plants and some parasites) require manual downloads and are subject to complex licencing.
- Occurrence records are point data and as such of limited use for an animal welfare hazard map, as they only pinpoint locations where samples were found, but provide no information about absence or a likelihood of occurrence. To be useful for hazard mapping, they would require conversion to heat maps or be enhanced through the application of clustering techniques, for example the Density-based spatial clustering of applications with noise (DBSCAN) or k-Nearest Neighbors (KNN) algorithm.
- Elements spanning multiple States and Territories are in disparate catalogues and formats. To visualise the entirety of the wild dog fences or stock route networks in Australia required significant search effort and three different techniques (ArgGIS API, Overpass API, SHP file).
- While the availability of detailed soil datasets and maps has improved in recent years, soil test data are unreliable determinants of micro-nutrient deficiencies, and the knowledge of micronutrient availability from pastures at a given point in time in relation to animal health is limited (Brennan et al., 2019).

- Access to shade and shelter affects the welfare of cattle in hot weather (Rosselle et al., 2013), therefore cattle grazing in a treeless pasture would be more exposed to weather extremes than cattle having access to trees and shrubs, even in temperate climates (Van laer et al., 2014). Vegetation can also shelter from rain and wind on cold days. The modifying effect of tree and shrub cover is an additional complexity that needs to be considered.

Notwithstanding the challenges, the dataset search and visualisation also uncovered new opportunities.

Occurrence records combined with environmental data such as topography, soil, vegetation, climate and others can be used in species distribution models (SDMs) (Franklin, 2010). Many examples were found in the literature of application of SDMs to diseases and parasites of cattle, for example Anthrax in Australia (Barro et al., 2016), liver fluke in Columbia (Valencia-López et al., 2012) and cattle ticks in Zimbabwe (Sungirai et al., 2018). There are also several studies using SDMs to predict the effects of climate change on species distributions. As models and data exist, there are substantial untapped opportunities to create relevant distribution maps and publish them as geospatial layers, which could then be incorporated into a livestock welfare hazard map.

Other opportunities for using public data for livestock welfare applications exist if it is federated with data from other sources. Arguably the greatest potential would be the use of on-farm records and sensor data in conjunction with environmental welfare hazards. However, there is potential in crowd sourced data as well, which could be using feeds from social media APIs to “listen for” key words, or it could be citizen science data collected from a public portal.

PLF is improving many aspects of the global livestock industry, including the welfare of animals, mainly through advanced tracking and monitoring applications (Jukan et al., 2017). The acquisition of ever more or better data is not a panacea though. Rojo-Gimeno et al. (2019) challenged the assumption that the value of information derived from PLF technologies is driven by more precise information, but concluded that this value is farm-specific, depending on farming practices and requirements, available information and the involvement of advisors. Also, the use of PLF technologies does not always translate to better welfare outcomes (Werkheiser, 2018), unless it is an integral part of good farm management. In addition, welfare evaluations of extensively managed sheep showed that even experienced personnel sometimes fail to detect welfare issues (Munoz et al., 2019). We argue that public datasets are an untapped resource that can provide additional valuable information to complement sensor data and human observations in achieving better animal welfare outcomes in extensive grazing systems.

Looking at other domains, there is little doubt that new insights can be gained from the federation of multiple datasets and the subsequent analysis and visualisation. When hurdles such as availability, privacy and interoperability have been cleared, there still remain issues to resolve, such as varying spatial or temporal scope and resolution, accuracy and reliability, different methods of measurement and timing of measurements. To allow aggregation of several datasets it is likely that some data cleaning and rewriting is necessary, requiring both information technology and subject matter experts. This would facilitate the removal of errors and out of scope data points and any translation of values to match up data sets. Yet, caution is still needed when looking for insights from federated datasets. Correlation could be mistaken for causation while data for important factors may be unknown, overlooked or unavailable. Additionally, the absence of data can have different meanings which affect the overall insights gained (Garrett, 2013).

Nonetheless, in view of the potential gains, we investigated the current availability of public datasets related to a set of welfare elements, based on current animal welfare standards in Australia. While useful data were found for most of the welfare elements, the quantity and quality varied substantially, and national datasets were generally of a lower resolution than those for states and territories, or for regions. Where regional datasets were provided by multiple agencies, a lack of consistency of data, metadata, spatial resolution and data currency was found. The harmonisation of several such datasets would require considerable effort to bring them to a common standard.

The effects of farm animals on the environment are recognised (de Vries & de Boer, 2010; MacLeod et al., 2018; Rolfe et al., 2016) and PLF is seen as a suite of tools that can be used to mitigate the undesirable effects of livestock farming on the environment (Tullo et al., 2019). Yet, while it is understood that the environment affects farm animals, particularly in the “natural environment” of extensive livestock systems (Petherick, 2006), the literature is sparse with regard to using PLF to measure or predict the effects of the environment on farm animal welfare, while in contrast, intensive animal farming systems extensively use PLF to measure as well as control the environment of animals (Berckmans, 2014). Petherick and Edge (2010) discussed the challenges to welfare assessments of extensive livestock from a management perspective but also note the importance of environmental factors. This study demonstrates that the research gap in extensive farming systems could be closed by using public datasets to determining environmental threats to animal welfare.

5.1.5 Conclusion

PLF is primarily intended to measure individual animals (Berckmans, 2014) and indeed it has been suggested that the definition of a PLF tool is the continuous high resolution measurement of animal traits (di Virgilio et al., 2018). Authors across PLF literature are in agreement that sensors on animals provide valuable information about the current physiological state of individuals, which provides insights on welfare. On the other hand, although such sensors may alert staff to animal welfare issues as they occur, for example an elevated body temperature indicating a disease, they do not issue a warning *ex ante*, nor do they provide information about the underlying cause of the symptom measured. This raises the question whether the definition of PLF should be confined to proximal sensing only. We argue that it should be defined more broadly and include technologies and data sources that contribute to improving animal production and welfare. More specifically, applications incorporating federation of data that would enable a manager of cattle and other grazing animals to have knowledge of environmental conditions that would likely result in poor welfare and compromised production.

Since animal welfare hazards have interdependency (Figure 5.9) and their importance varies with time and place, there is potential to use public data sets (and perhaps utilising artificial intelligence methods) to map spatio-temporal animal welfare hazards. We propose that such hazard maps could take the form of a geospatial portal to provide visualisation and location information about environmental factors affecting livestock welfare. Such a portal could provide useful information as is, or be used in conjunction with remote sensing data, if such data are available in interoperable formats. However, it would require open data that had the coverage, resolution and temporal currency to provide the confidence in the results. Most importantly, it would require the adoption of FAIR data principles by the data custodians to maximise their data available for the extensive livestock industry.

Increasing knowledge of environmental influences on livestock welfare has several key benefits. Firstly, it can directly inform on-farm decision making to improve animal welfare, and thereby production. Secondly, it can provide the evidence-base for making good welfare decisions that address the key dimensions of the social licence to operate, being legitimacy, trust, transparency and communication (Duncan et al., 2018). Thirdly, strong linkages between climate zones and livestock parasites and related diseases indicate that climate change will precipitate changes in known areas of prevalence, which is of concern for the livestock industry (Fox et al., 2015; Skuce et al., 2013). Bringing together climate forecasts, livestock diseases and parasite datasets, applying SDMs and providing the output as geospatial layers that can be queried and visualised can help the livestock industry plan for better welfare outcomes during climate change. Where datasets are not only open, but maintained and updated by their respective custodians, changes would automatically reflect in the information shown in a livestock welfare portal.

5.2 Supplementary material

Supplementary material related to the livestock welfare case study, which was submitted with the journal submission of the manuscript in Section 5.1 can be found in Appendix 2.

5.3 Epilogue

The overall goal of the case study was to test if the quantity and quality of available public data in Australia is sufficient to inform decision support in extensive livestock farming. Animal welfare was chosen because the literature review identified it as a topic of high importance but with little work done in the way of decision support and no examples of welfare-supporting precision farming applications for extensive farming industries. Beef cattle were chosen as example species for the case study as they are farmed throughout Australia.

The case study design implements a novel approach that takes the defining elements of animal welfare unrelated to farm management from the relevant Australian welfare standards and translates these to use in a dataset search. The search results are tested in a geospatial application and analysed for potential usefulness in a conceptual welfare hazard map of Australia. The analysis shows some gaps (some welfare elements could not be addressed) and limitations (temporal and geographic scales) in the data found, but yields useful data and identifies additional opportunities towards implementing a hazard map as a geospatial application.

6 Development of a conceptual grazing animal welfare portal

One of the outputs from the animal welfare case study in the Chapter 5 is a list of datasets of welfare hazards, viewable as geospatial layers in the desktop program QGIS. This chapter advances the concept of a livestock welfare hazards map by presenting a conceptual geospatial web portal that uses the case study datasets as well as other relevant geospatial layers. It demonstrates possibilities for use at farm scale and at regional scale. It is intended as a pilot project with a view to future development into a full-scale web application.

6.1 Introduction

Maps are a rich visual source of information, suitable for communicating environmental risks (Severtson & Burt, 2012). The purpose of hazard maps is to provide information to end-users that would inform and aid their decision making and planning, especially related to risk. Multiple examples exist of geological, climatological and natural disaster hazard maps for various geographies, but examples of animal welfare hazard maps could not be found. Lindell (2020) distinguished between chronic hazards and acute hazards, with the latter relating to current situations and warning of imminent threats. The nature of most of the available (publicly open) datasets for livestock welfare relate to chronic hazards.

Despite open data policies being implemented by many governments around the world, many of the open spatial datasets remain invisible to most users because they require skills and software applications to access and view them (Dahlhaus et al., 2017)

Without knowledge of the datasets involved, it is difficult to grasp their relevance to livestock welfare, or to imagine their visual properties. Indeed, even with detailed knowledge of the data and their metadata this is a challenge. Humans are visually oriented and can quickly make sense of a picture, while a table of data takes much longer to comprehend. The old adage that "a picture speaks a thousand words" also holds true for maps and geospatial information, but visual cognition within maps is influenced by several factors, which have to be taken into account when designing the visual interface of a hazards map (Severtson & Burt, 2012).

The case study datasets (Chapter 5) were viewed and tested in QGIS, but as a desktop program it cannot publish this visual information. To be accessible to other users, it is necessary to set up a geospatial application that is hosted on a public server and can be viewed in a web browser. The goal of this research is to pilot this livestock online welfare hazard map with the following functionality:

- Regional scale: visualising welfare hazards for a different grazing animal species (cattle only in the demonstrator version)
- Farm scale: identify welfare hazards at a given location
- The inclusion of a variety of other useful PLF decision support information from other data services, such as past weather and climate, boundaries and location of services
- Links to other relevant data portals

Although the current implementation of the welfare hazard map is for demonstration purposes and lacks full functionality, future versions are envisaged to have multiple potential users, being researchers, livestock farmers, industry bodies, planning authorities and others.

6.2 Methods and results

The application demonstrates the use of public datasets for livestock welfare decision support, using a combination of datasets found during the case study dataset search in Chapter 5, additional relevant datasets and other potentially useful information.

The welfare hazards map was developed from the code base for geospatial portals written by CeRDI. It is built on open source software including PHP on the server side, and HTML, CSS, JavaScript and the Bootstrap[35] framework on the client side, as well as several JavaScript libraries such as OpenLayers[36] and Jquery[37]. The map layers are loaded via Asynchronous JavaScript and XML (AJAX), using custom libraries and tools also developed by CeRDI and used with permission.

The datasets displayed in the portal have already been tested in QGIS (QGIS.org, 2020) as documented in Chapter 5. Whenever possible, datasets are sourced directly from OGC compliant web services, being Web Mapping Service (WMS) or Web Feature Service (WFS) endpoints. For datasets available only as file downloads, these were obtained and where necessary, clipped to the extent of Australia, styled and uploaded to a GeoServer[38] instance maintained by CeRDI[39], which then provides these datasets as WMS or WFS services to the geospatial portal. Figure 6.14 illustrates the generalised systems architecture of CeRDI's spatial data infrastructure that enables the flow of data from various sources through to the end users.

[35] https://getbootstrap.com/
[36] https://openlayers.org/
[37] https://jquery.com/
[38] http://geoserver.org/
[39] https://geo.cerdi.com.au/geoserver/web/

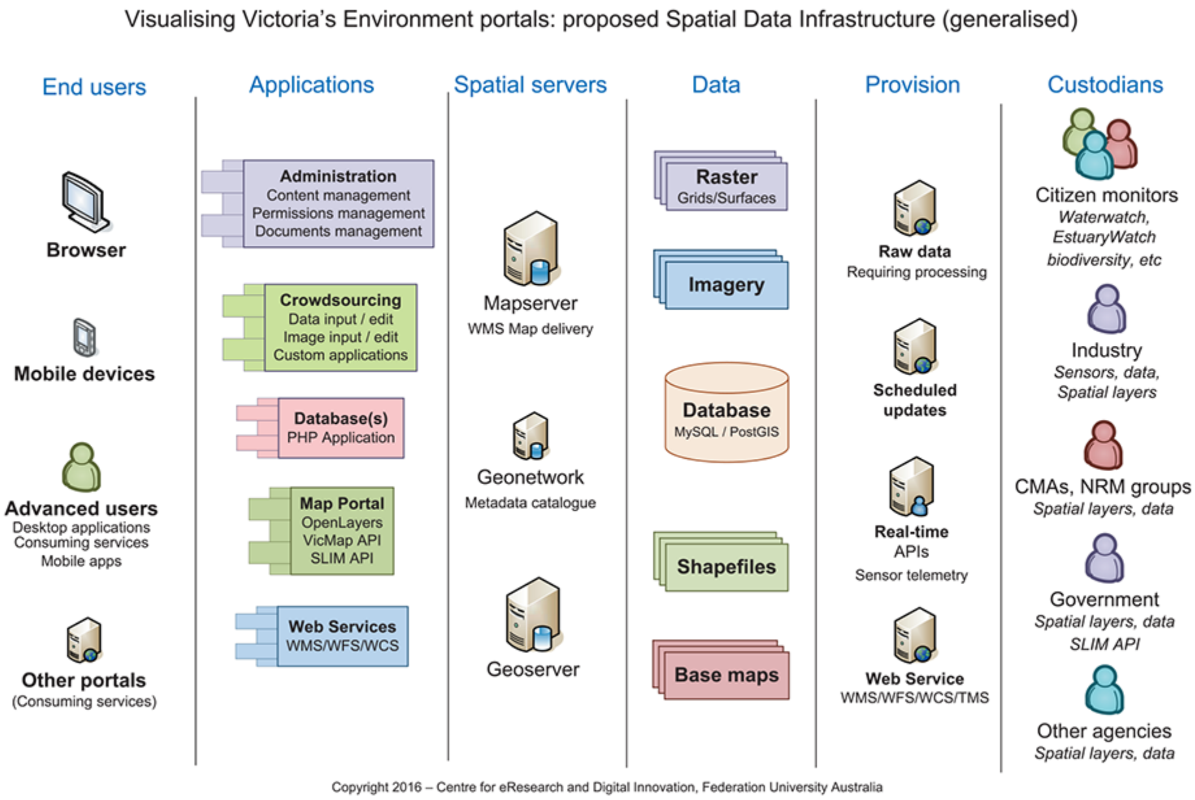

Figure 6.14 – CeRDI spatial data infrastructure. Reprinted from Dahlhaus & Thompson, 2016: Visualising Victoria's Environment: Collaborative development of inline tools for State of Environment reporting. CeRDI Discussion paper prepared for the Office of the Commissioner for Environmental Sustainability, Victoria. Reprinted with permission.

The demonstration version of the welfare hazards is available at:

http://phoebus.cerdi.edu.au/

Screen shots below show various aspects of the portal. Figure 6.15 shows the interface when the map is opened, with information about the portal on the left-hand side. The map has been zoomed into the southern part of Western Australia, displaying two datasets that have been selected from the layers panel: a national dataset of water bodies and areas of flood risk for Western Australia.

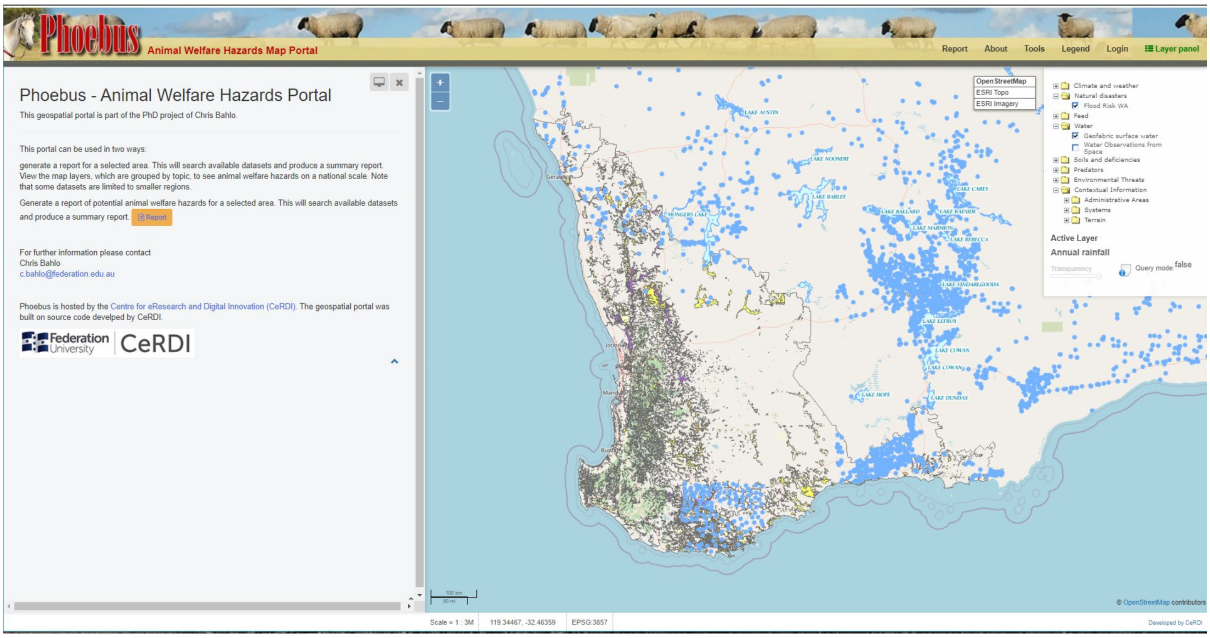

Figure 6.15 – Portal screenshot depicting national and Western Australian layers

Figure 6.16 shows the report tool panel on the left, which explains how to generate a report and offers several selections, such as drawing a polygon (pictured) of the user's region of interest, or selecting a point or line and searching within a user-nominated buffer distance around that point or line. The map shows where such a selection has been made. The user, on clicking the "Generate Report" button, will see a report of the hazards for the selected area, sourced from the welfare hazards and related datasets that are included in the portal. In this way a farmer can search the area around their property.

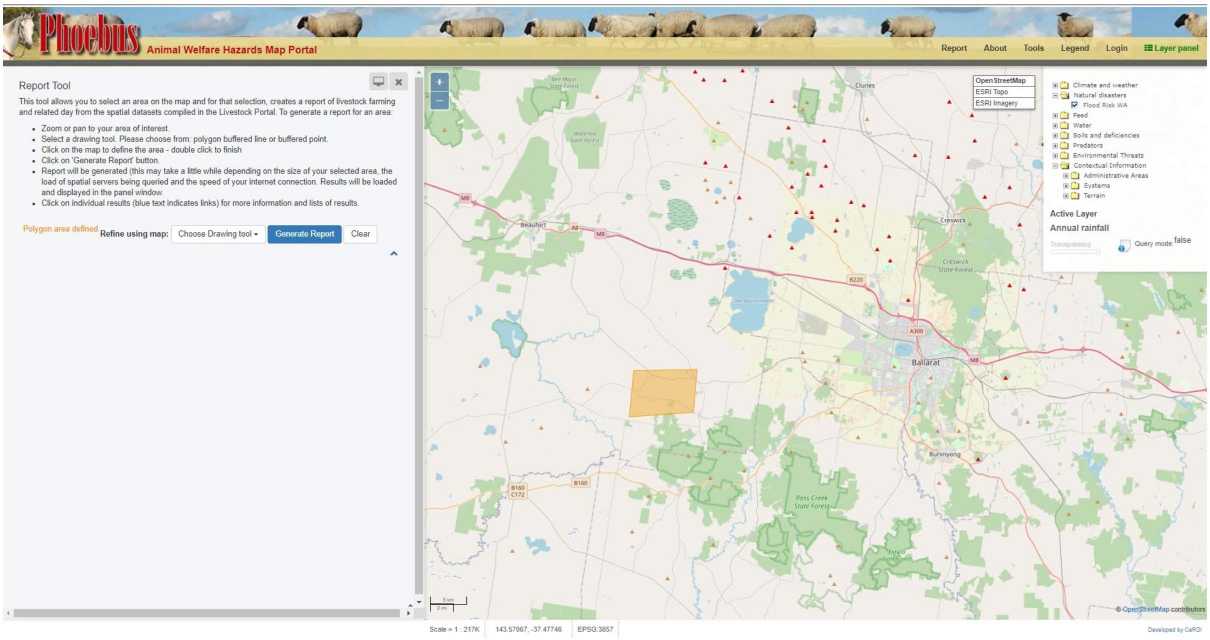

Figure 6.16 – Portal report tool and selected area

6.3 Discussion

The implementation of a livestock hazard map was successful in as far as it was technically enacted and performs (as a demonstrator with limited capabilities) the desired functions of showing available layers and reporting a list of potential hazards for user-selected areas. User testing was not conducted, nor can any conclusions be made regarding the likely uptake by users who can benefit from it. These aspects require further investigation involving usability testing and feedback from users as well as expanding the number of layers for additional grazing animal species. Further, the data displayed in the portal was taken on face value and was not verified using field data, which was out of scope. Such validation would also require further investigation, particularly in relation to NDVI indicating feed availability.

However, despite the limitations, the map portal is a potentially significant contribution to grazing animal welfare in extensive livestock systems, as well as rangeland livestock systems. The identification of hazards within a specified area is useful for existing livestock farms. The argument that a good manager should know the animals and the environment and be “on top of” potential environmental welfare threats can be countered with a number of opposing arguments such as that the environment is not static because climate and landscape variations occur from year to year and season to season and over longer periods. A farm manager, even with the benefit of local experience, is unlikely to be aware of all environmental hazards. A change of livestock type, of farm manager or farming practices can also reasonably be expected to impact the way that livestock are managed and affected by the environment, be it that new staff are unfamiliar with the locality or that a new livestock species or breed or age group has different risk factors. The livestock industry will be impacted by changes to the climate (Henry et al., 2012; Rojas-Downing et al., 2017) and accelerated anthropogenic changes to landscapes (such as urbanisation and industrialisation), which will add urgency to obtaining reliable information about environmental hazards. These information needs could be served by a livestock hazard map.

A welfare hazard map could also be useful when considering a new location for a livestock enterprise, or for selecting stock to run on a new or existing property. Matching animal types to the environment with regard to heat stress and disease tolerance (Rojas-Downing et al., 2017) has the potential to not only mitigate possible welfare issues (Hoffmann, 2010), but also increase production (Dikmen, 2013), thereby minimising the use of labour (for management, intervention and treatment) and chemicals that are required to prevent or treat diseases and parasites. Less interventions, less medications and less chemical treatments are desirable from a sustainability and environmental perspective as well as food provenance.

In addition to providing benefits to livestock farmers, principally by the use of the reporting tool, the hazard map could also be used by planners who require hazards information for resource allocation and future planning decisions. Such users are also likely to use the map layer selection panel to provide visual overviews of larger area.

It is noted that insufficient datasets currently exist for beef cattle to fully support a welfare hazard map. Other livestock species like sheep and goats may be supported by more datasets but were not investigated in this research. Although limited, there was sufficient data to implement a conceptual welfare hazard portal as the foundation for future work.

The datasets currently available and used in the portal are static in nature and therefore cannot show changes over time and there is limited capacity for disaggregation. However, should datasets with more spatial and temporal resolution become available, the ability to visualise data based on spatial queries and changes over time can be added, which would also address the problem of changing boundaries. While the hazard map is not currently intended to include real-time streaming data, it is technically feasible to add this functionality if such data were available via suitable services such as one or more of the OGC's Sensor Web Enablement (SWE), Sensor Observation Service (SOS), Sensor Planning Service (SPS) or Observations and Measurements (O&M).

The literature showed that research is progressing with new models for parasites and disease prevalence, climate and climate change, soils and soil deficiencies, toxic plants prevalence and natural disasters. Unpublished datasets that underpin or are the output from such research may be made publicly available in future. It is also anticipated that the global push for FAIR data will improve the availability of suitable data. Lastly, data could be directly contributed by potential collaborators for the purpose of extending a welfare hazards portal.

7 Discussion

7.1 What are the lessons learned and insights gained for data and interoperability standards in livestock farming?

The general aims and objectives of this thesis (Section 1.2) are to investigate the status of interoperable standards in precision livestock farming and the potential of using public data to support decision making, particularly in relation to grazing animal welfare.

The main discussion points are:

1. Data interoperability standards in PLF – where are we at?
2. Public datasets for PLF – what quantity and quality is available in Australia?
3. Public datasets for grazing animal welfare – are they sufficient and useful?
4. Technical challenges related to using public datasets for PLF

7.1.1 Data interoperability standards in PLF – where are we at?

This study started with a need to better understand the level of uptake of PLF technologies and open and interoperable data standards in the extensive livestock farming industry and the theory that existing available public datasets are useful, and indeed used, in PLF applications.

The review of literature, data standards and PLF applications in extensive livestock farming provided an overview of the status of PLF, giving an insight into issues such as technology acceptance and uptake, the challenges of using PLF in extensive or rangeland farming systems and more specifically, the related data requirements and challenges. The industry's needs in terms of data acquisition, management and sharing, as evidenced by the literature, showed that data sharing, interoperable data standards and public data are considered useful, but these needs are not yet sufficiently met. Domain specific open data and community-based open interoperability standards do not exist, though some open data vocabularies were found. However, more general data interoperability standards (for example OGC standards and open data vocabularies) and metrics, such as FAIR principles, can be applied to the livestock farming domain in place of domain specific standards and fill this gap. It could be argued that these standards work very well and that specific standards may not be needed beyond domain specific vocabularies.

The review contributed an overview of data interoperability for PLF in Australia that provided answers to the first of the four research questions. It also contributed to the remaining research questions by providing a base understanding of the issues within the domain. With regard to the sharing of private data and the use of accessible public data on the other hand, further investigation is called for. The discussion arising from the literature review raised two main questions. One is related to the value proposition(s) and how the owners of private data could be motivated to share their data for the greater good. This question falls within the realm of the social sciences and necessitates studies in its own right. Indeed there are many studies shown in the literature that give insight into this topic, for example Paustian and Theuvsen (2016), Robinson et al. (2019) and Yost et al. (2018). However, the focus of this study was the other question arising from the literature review: whether available public datasets can provide or add to the information needs of livestock decision support systems. To answer this question, it was necessary to determine data availability, data quality and usefulness, or in other words, fitness for purpose.

7.1.2 Public datasets for PLF – what quantity and quality is available in Australia?

It is clear from the research that the quantity of public data related to extensive livestock farming is substantial. The discovery of over 400 unique Australian datasets in response to searches for terms including cattle, sheep, livestock, grazing, feed, fodder and pasture shows that public data can and should play a greater role in PLF, as envisaged by Capalbo et al. (2016). It is noteworthy that public data about weather, climate and soils were not included in the dataset search, which was deliberately specific to livestock data. As they represent additional sources of public data relevant to the domain, this further strengthens the case for including public datasets in decision support systems. Jones et al. (2016b) stated that public datasets are in use in agricultural decision support tools, but only in relation to economic and environmental performance. They also mentioned that data limitations exist with regard to livestock farming, holding up the development of models and data federation for decision tools. This research appears to indicate that the number of available datasets is no longer as much of a limiting factor and may facilitate decision support beyond economic and environmental livestock farm performance.

Public data mostly originates from government departments and research institutions which means it has undergone some quality checks and data cleaning, therefore it can reasonably be expected to be accurate and trustworthy. However, no such assumption can be made in relation to data formats, provisioning, licensing and other data quality aspects. This research shows that the available public data varies considerably in quality when viewed through the lens of FAIRness.

The FAIR principles were chosen as quality metrics as they are an emerging de-facto standard for data quality (Stall et al., 2019) and ongoing efforts promote the uptake across all domains (Koers et al., 2020). Of interest to this research are the established assessment frameworks to facilitate compliance testing, and particularly the FAIR Evaluation Services, which allowed automation of this task. It was observed that some of the results were inconclusive or incorrect, necessitating further investigation of the metadata in the datasets found in the search. This indicates that some further work may be needed to extract the necessary information on the one hand, and on the other hand to ensure that data custodians and catalogue maintainers provide well-structured metadata. While interoperability standards and other FAIR metrics should be overarching, it has been recognised that domain specificity will require the development of specific tests (Wilkinson et al., 2019), and this test case supports that view. The need for specific quality metrics has also been noted in data quality assessments not related to FAIR data (Pipino et al., 2002).

However, despite the challenges in applying the tests and interpreting the results, it is clear that many of the datasets ranked well in the accessibility and findability metrics, but more poorly in interoperability and reusability. This is not entirely surprising as the first two characteristics are relatively easy to achieve merely through listing a dataset on the internet with a permanent identifier and providing basic metadata, whereas achieving the second two characteristics of FAIR require extensive metadata, licensing information and provision of appropriate data formats. While these findings take some of the shine off the prize that is the number of datasets found, the results still indicate that most of the datasets are FAIR enough to contribute to PLF. It is hoped that the increasing uptake of FAIR principles in the agricultural domain (Levett et al., 2019) will see improvements in the level of FAIRness in domain datasets over time.

Notwithstanding the issues encountered during the quality assessment, the review outcomes and the insights arising provided an overview and detailed information about the status of Australian open data within the extensive livestock domain, which adds to the current body of knowledge and may assist in developing targeted approaches to improving data interoperability within the domain. Additionally, both the methodology and the specific tools developed to facilitate the systematic dataset are valuable beyond the systematic dataset review undertaken, which was shown during a systematic review of soil datasets outside this study, as well as for the grazing animal welfare case study.

7.1.3 Public datasets for grazing animal welfare – are they sufficient and useful?

The systematic dataset review and quality testing provided an overview of public datasets with in the domain, but didn't provide clarity about availability and usefulness of public data to support animal welfare in extensive farming systems. The livestock welfare case study showed that some aspects of welfare can be informed by public datasets while others lack any data or the data is not useful enough for the purpose. However, it could be demonstrated that a grazing animal welfare hazard map is possible, even though there are some data limitations at the current time.

Interdependencies were found between some of the welfare elements, welfare indicators and soil, which is not directly related to welfare, but literally and figuratively is the basis of most farming activities. These interdependencies did not affect the data search but need to be taken into consideration in a welfare hazard map. Some of these interdependencies are addressed by existing models for species distribution, soil types and others. Particularly with regard to the prevalence of diseases, parasites and poisonous plants, which weren't well represented in the datasets available, there is huge potential for collaboration with researchers (in both the public and private sectors) who can contribute geospatial layers constructed from observation data, climate data and species distribution models.

Although a number of challenges were identified with regard to useful public data for the welfare hazard map case study, there are also opportunities for enhancing available public data and for including other data sources. The increasing emphasis on getting animal welfare “right” so that the social license to operate for livestock farmers is retained, means that animal welfare decision support is highly desirable. An animal welfare hazards map has the potential to provide valuable information to livestock farmers to help achieve this. It could also serve policy makers when viewing overlapping welfare challenges on a regional scale. The contribution of this study is a novel method to translate welfare indicators to a public dataset search, which can be replicated for other grazing animal species and geographies. The second contribution from this case study is an insight into the availability of suitable public datasets for welfare in extensive livestock farming in Australia.

The final step was the development of a conceptual welfare hazard map in the form of a geospatial portal, and it was possible to demonstrate the usefulness of public data both at a farm scale and at a regional scale. At farm scale, the application allows querying the map at a selected location to obtain a list of likely local hazards, whereas the visualisation of the layers provides a regional overview of potential threats.

7.1.4 Technical challenges related to using public datasets for PLF

During dataset searches for two different purposes with different scopes, and the subsequent attempt to use the case study datasets in a welfare threats map, technical challenges wee encountered. These are largely reflected in the FAIR rankings, where low scores in interoperability and reusability directly translate to difficulties in terms of federating such datasets with other data within PLF applications. A thorough analyis of the low ranking datasets was not undertaken due to time constraints. However, due to finding some datasets via manual searches as well as via automated searches, it was apparent that the lack of metadata in the automated search results (for example dataset distributions, licencing or geographic extent) was sometimes due to limitations of the API output, and at other times because such metadata does not exist.

Considerable time was spent on finding and reading documentation about the API endpoints of data catalogues, an effort that had to be replicated for each API type. Technical expertise was required to interpret documentation and develop scripts to parse the output returned by the catalogue API (which was either JSON or XML) into a human-readable format. Further, it is likely that these scripts will need maintenance as catalogue APIs endpoints change over time. As the output from different APIs varied, some manual processing was required to combine the metadata records. Manual processing in conjunction with the use of spreadsheet sort and filter functions was also needed to remove duplicates. This situation could be improved if all public datasets were accessible via the same API or at least using the same standard, be it CKAN or Magda or OpenAPI. Also, endpoints should be well documented and provide standardised access to all metadata fields. This would considerably improve the ability to automate searches and allow the consumption of metadata by machines as well as humans. Standardised metadata records would also facilitate the search for specific geographies and temporal extents, which would greatly enhance the usefulness of public datasets in PLF applications.

7.2 Where to from here?

In agriculture, one of the greatest challenges is said to be the procurement of reliable data for decision making support (Jones et al., 2016b), yet the observation has been made that public data is highly underutilised in agricultural decision support systems. As multiple challenges exist in measuring welfare in extensive livestock (Petherick & Edge, 2010), the exploration of the presence and usability of public data to inform animal welfare is desirable. These factors provided a strong motivation for undertaking a review of public datasets and investigating opportunities for the use of these in grazing animal welfare and PLF applications.

A grazing animal welfare hazard map could provide information useful at farm level, answering the question: what are the local hazards? It could also inform users at landscape level by providing a visual overview of hazards, which could be used by planning authorities or industry bodies. While this study focused solely on the public data sources that are available, it is to be expected that greater value can be provided if private data sources will complement and enhance the hazard map both at farm and landscape level. Capalbo et al. (2016) considered at length the need to bring together private and public data for both farm scale and landscape scale decision support and analytical tools. The inclusion of private sector data in the animal welfare hazards portal could be facilitated in several ways. Some possibilities are:

The portal could be extended in functionality such that users can sign up and record observations, thus adding their own local knowledge to the map, for example on-farm observations of diseases, toxic weeds, chemical spills or areas that are dangerous to animals in certain conditions. The combined view of such local observations and regional public data would add to the value of a hazard map for the user and facilitate better decision support (Jeppesen et al., 2018). Further, if local observations can be linked to environmental conditions, then the addition of some server-side logic could deliver warnings about impending welfare threats. One example is a farm dam on the property that becomes muddy and traps livestock when the water level drops too far as a result of dry weather. Such as hazard could be entered into the map and linked to rainfall records to raise an alert before animal become trapped. Further possibilities include linkages to virtual fencing systems which could be set to automatically exclude dams or other hazardous areas for livestock in certain conditions. In addition, sensors on animals or around the farm connected via IoT networks and other novel PLF technologies, for example automatic parasite load detection (Cortivo et al., 2016) could also be used to contribute data into a welfare hazards map, assuming all data sources are standardised and interoperable.

The abovementioned application does not automatically allow a user's data to be shared. While it provides advantages to the user in that limited form, a data sharing arrangement would enhance the use and re-use of private data contributed by many users. The value proposition is that users benefit from the data of other users by sharing their private data in a manner that protects their interests (for example through the application of anonymisation, aggregation or averaging). There are complexities in relation to governance, data stewardship, information models and social architecture that pose challenges to private data sharing, which necessitates the creation and adoption of data privacy and sharing policies (Wiseman et al., 2019) and obtaining agreement from users (Yost et al., 2018). Looking over the fence into related domains, it can be seen that such sharing arrangements have been implemented successfully, albeit after a lot of preparation to inform and engage potential participants.

The abovenamed complexities also relate to research data, which additionally may be subject to other constraints, such as complex data ownership and sensitive data. On the other hand, some datasets are simply not FAIR enough to be re-used. These issues are recognised in the broader domain of agriculture, where collaborative projects like AgReFed seek to enable FAIR agricultural data from the Australian research community (Box et al., 2020). The AgReFed project's enactment phase has been completed and funding was secured to enable a transformation in agricultural research data collection, description and dissemination[40]. This is expected to improve decision making in agriculture overall and therefore most likely also in the livestock farming subdomain.

Another exciting opportunity for additional data to contribute to agricultural decision support, such as a welfare hazards map is citizen science (CS) (Janssen et al., 2016). CS is an approach to data gathering that has been successfully used in many different domains including agriculture (Ryan et al., 2018), for example to track agricultural pests (Ryan et al., 2019). However, the success of a CS application is linked to a suitable user interface within the portal for recording of observations, a campaign to bring the application to the notice of potential participants, and the championing of project by relevant bodies to motivate participants, while providing personal satisfaction and rewards to participants (Phillips et al., 2019). The idea of using CS to contribute to an animal welfare portal was explored in a conceptual project presented during GovHack 2020 and merits further investigation.

However, to ensure the trust of industry, consumers and researchers, certified objective data is essential, therefore data contributed by the private sector and citizen scientists requires checking and moderation. This would need to be provided by a governance

[40] https://doi.org/10.47486/PL005

structure and may require the registration of trusted repositories, for example Core Trust Seal (Edmunds & Leasor, 2019) or Five Safes (Arbuckle & Ritchie, 2019; Desai et al., 2016). Incorrect data could be entered due to human error or subconscious bias, but there is also a danger of deliberate wrong data being contributed by persons who attempt to promote or defend particular causes, as animal welfare has become a battleground for ideological beliefs (Parliament of Victoria, 2020).

While not identified within the environmental welfare elements sourced from the cattle welfare standards, and therefore not included in the dataset search, the location of abattoirs and livestock exchanges could also be relevant to a hazard map. Distances by road between livestock farms and markets or processing facilities determine travel time for animals. The transport of animals in Australia is covered by separate welfare standards and guidelines[41] and reference is made to acceptable travel and resting times. Particularly for the more remote parts of Australia, proximity information for such facilities may be useful, which would necessitate sourcing location information and calculation of transport distances by road (c.f. geographic distance).

Other opportunities for enhancement of a livestock welfare application are visualisation of the output of new models, such as SDMs for parasites and toxic plants, predictive models for weather events and climate change, matching genetic potential against environmental factors, and disease spread. Such models could be supported by ML and Artificial Intelligence (AI). Elith et al. (2006) compared methods of predicting species' distributions from occurrence data and noted that presence-only data presents particular challenges. This

[41] http://www.animalwelfarestandards.net.au/files/2015/12/Land-transport-of-livestock-Standards-and-Guidelines-Version-1.-1-21-September-2012.pdf

is of relevance, as the datasets found during the case study were predominantly presence-only records. Therefore, a first step towards improving the predictive ability of models would be a systematic sampling (at to be determined, relevant geographic and temporal points) for important diseases and parasites. The authors point out that while modelling is unable to provide the same level of information as detailed and ongoing data collection, but that the inclusion of more detailed data (both occurrence records and related environmental data) will result in better model output. The observations from the dataset search in the case study are that very little current and detailed data exists in relation to diseases and parasites for cattle in Australia, while environmental data is much more readily available. The authors also refer to the need for accurate and timely data related to livestock for the purposes of predicting potential disease spread. While census data exists, more research is needed to understand whether this is sufficiently detailed to be used in modelling.

The value of a livestock hazard map that federates public and private data is two-fold. Firstly, there is a direct benefit to farmers (local scale) and planners (regional scale). Secondly, public data along with user data that is contributed can potentially be used to develop better models and train AI algorithms to enhance the level of useful information and predictive capabilities of the hazard map.

8 Conclusion

This research began with the premise that global food security is an overarching goal that is accompanied by challenges for agricultural food production and livestock farming in particular. PLF increasingly contributes to solving those challenges, but currently less so in extensive livestock systems despite its global geographic size and economic contribution. Interoperable data standards and the adoption of FAIR data principles are considered essential to underpin future PLF development to facilitate the collaborative use and re-use of public and private data.

This research identified four research questions related to PLF, interoperable data standards and FAIR data during a review of the literature. This chapter is a summary of the outcomes for each of these research questions, the contributions made and some concluding final observations.

1. **What is the status of data interoperability for the precision livestock farming domain?**

Data interoperability has two aspects: standards and datasets that may or may not conform to those (or other) standards.

The first aspect (the standards) was investigated in the review of global literature, data standards and PLF applications. The consensus of the literature is that the entire agricultural domain is only in the infancy of developing specific data interoperability standards and vocabularies, and livestock farming is particularly underrepresented. Subsequent searches of the literature have not indicated that this situation has changed significantly.

However, as the use and re-use of datasets is a theme common to most knowledge domains in recent times, interoperable data standards have been developed and are in use. Some of these standards are domain-agnostic and therefore applicable to livestock farming. From a data management point of view, these interoperability standards are mature and adequate for the task regardless of the domain they are used in, and perhaps it is more important to develop relevant metadata vocabularies rather than specific data standards for livestock farming, or even agriculture as a whole.

The second aspect (conformance of public datasets to interoperability standards) is related to the third research question and was investigated through a systematic dataset review in Chapter 4; the results are noted below.

2. **Where and how can public datasets relevant to decision support within livestock farming be found?**

This question was addressed within the data search section of the systematic dataset review in Chapter 4. The answer is that relevant public data can be found within several public data catalogues, many of which are curated by government (federal and state level), others by industry associations or research institutions. The assembly of a list of catalogues relevant to livestock farming required some domain knowledge as well as Internet searches. A listing of data resources for agricultural sub-domains like livestock farming may in itself be of value for future searches. Findability, which is the first aspect of FAIR, can be improved through placing adequate metadata records in public catalogues, which would lessen the reliance on domain knowledge in conducting dataset searches.

Having identified potential data sources, it was necessary to determine the most efficient method for querying those data catalogues to find datasets relevant to livestock farming.

While some data catalogues required manual online searches, a surprisingly large number of catalogues provide public APIs that enable efficient bulk queries based on full text or keyword searches. The search methodology that was developed yielded 419 Australian datasets for the search terms that had been selected for the search. As different APIs are in use across catalogues, multiple scripts had to be developed to facilitate querying these. All scripts that were used in the systematic dataset search are reusable and have been released into the public domain.

Only one data catalogue queried was related to the livestock domain, while all others have a broader scope. The search yielded interesting results, showing that certain search terms were more strongly represented in some catalogues and that duplication of datasets was common between some data catalogues but not others. The largest data catalogue, which also had the most duplicates in other catalogues is data.gov.au (the Australian Government catalogue). Duplicates also occurred when datasets were found for more than one keyword. As expected, the more specific the terminology, the less datasets were obtained in searches. The largest number of datasets was found for “grazing” and “livestock”, followed by “sheep” and “cattle”. It is noted that while the search terms were chosen with care to represent the livestock domain as a whole, a different set of search terms could yield quite different results. Therefore, while the results of the dataset search did answer the question about the quantity and quality of datasets currently, the development of a methodology to conduct such searches and assessments is likely to have more long-term benefits because it can be applied to other search terms or even other domains.

3. **What is the quality of these datasets, and can their FAIRness be determined?**

The second part of the systematic data search in Chapter 4 attempted to measure dataset quality through a FAIR assessment. The assessment of 419 Australian datasets found in the search was done with the help of an automated FAIR assessment tool and used custom scripts developed for this research.

The results from this assessment were not conclusive in some aspects of FAIR, as the assessment was unsuccessful in measuring five of the 18 FAIR metrics and was only partially successful in correctly identifying metrics related to findability and reusability. However, the results showed that high FAIR compliance was only observed for three of the metrics, while the remaining ten metrics tests were only passed by less than 50 percent of all datasets tested. Data licences and distributions (data type) were investigated by other methods. Only 44 percent of datasets have CC licenses. Distributions were shown to include only a small number of web services, but 54 percent used open formats and 40 percent of datasets were of unknown format.

These results indicate that the level of FAIRness in public datasets for the domain is only moderate, although it is unclear whether this applies to just the livestock farming domain in Australia (which was tested), or is representative of the farming domain in general (not tested). Caution has to be taken in interpreting FAIR test result percentages, as the result set of datasets was based on a very broad set of search terms. The results also indicate that domain-specific FAIR metrics may need to be developed to provide a better test of FAIRness of datasets.

The FAIR assessment was useful because it was the first quality assessment of public data within this domain, which may serve as a baseline for future assessments. The findings raise the question whether interoperability and reusability need to be addressed as a matter of priority, so that data that are found and are accessible are actually useful to farmers and researchers. Another aspect of usefulness is currency of datasets, which was difficult to ascertain due to metadata limitations, because descriptions ranged from dates to time intervals to no metadata at all. Other aspects related to data completeness and data veracity were outside the scope of the data quality assessment, which was centred on FAIRness, but these aspects should be investigated further to identify data challenges.

4. **What are the opportunities and the challenges to the use of public datasets in being used in decision support systems for livestock farming?**

Some of opportunities and challenges were identified in the initial literature review, but it left open the question whether available public datasets can provide or add to the data required for livestock decision support. A better understanding of the opportunities and challenges was gained during the case study, which is the attempt to answer the practical question: is the data available and is it usable to answer my specific livestock farming question?

The case study chosen was a topic that stood out during the literature review: animal welfare. The reasons for the importance of welfare in grazing animals was discussed in the literature review in Chapter 2 and in the case study in Chapter 5. The case study was conducted by identifying environmental welfare issues, mapping these to searchable terms and searching for relevant datasets, re-using the methodology and tools developed in Chapter 4. The goal of the case study was to create a grazing animals welfare hazard map using available public datasets.

The analysis in Chapter 5.1.3.3 discussed the limitations found within the public datasets on offer, which were a result of insufficient data, datasets lacking currency and insufficient spatial resolution. However, all but one of the environmental welfare issues that were considered in the case study yielded some data that could be mapped and would contribute to a welfare hazard map. The identification of gaps in coverage or lack of currency in itself was a useful exercise to determine where additional searches or targeted procurement of data is advised. The analysis concludes that while public data is currently not quite sufficient to support a grazing animal welfare map, it will be possible if more public data can be obtained. It also concludes that federation of public datasets with other sources, such as citizen science or private grower datasets has the potential to add value and create a more reliable and useful welfare decision support tool.

The animal welfare hazard map concept was further explored as a conceptual web application in Chapter 6. This application demonstrates the applicability and usefulness of some of the datasets found in the case study in Chapter 5 at a farm scale as well as regional scale in a geospatial portal. It is intended as a pilot project for future work which includes procurement of additional public datasets, agricultural model output, and federation with private livestock data with the goal of becoming a full decision support application for extensive livestock farming.

In summary, this research began with four research questions, which were addressed through reviews, data searches, a case study and a demonstrator geospatial portal. In answering those questions, a number of contributions were made to PLF, FAIR data, data discover and data search methodologies. A published review of data interoperability standards within the PLF domain and in a broader context determined technology adoption and data interoperability maturity in relation to extensive livestock farming globally. Developed for Australian extensive livestock farming, but applicable globally and across all domains, a methodology to systematically find and review open datasets was developed. This included strategies and specific methods to query a variety of Australian open data catalogues to allow for the acquisition of data and metadata for the livestock domain. Software scripts were developed and released into the public domain, which retrieve metadata from open data catalogues; these scripts were used in the systematic review of Australian livestock farming datasets. A review of FAIR assessment tools and use of FAIR metrics in conjunction with a reusable script developed for this purpose permitted measuring the level of FAIRness of public data in the livestock farming domain in Australia. The opportunities and barriers related to the use of public datasets to inform decision support in livestock farming were analysed through a livestock welfare case study. As the literature review had identified livestock welfare as an area not well supported in the range of available PLF applications, the case study also contributed to the research in animal welfare. This was supported by a proof of concept livestock welfare hazards map, which has future potential for public-private collaboration. This research also provided recommendations about data standards and FAIRness assessment in the livestock farming domain.

Appendix 1

This appendix contains information related to the systematic dataset review in Chapter 4.

Table 4.3 - API endpoints used in systematic dataset search

Name	Type	API endpoint
data.nsw.gov.au	CKAN	https://data.nsw.gov.au/data/api/3/action/package_search
data.sa.gov.au	CKAN	https://data.sa.gov.au/data/api/3/action/package_search
data.vic.gov.au	CKAN	https://api.vic.gov.au:443/datavic/v1.2/package_search
data.qld.gov.au	CKAN	https://www.data.qld.gov.au/api/3/action/package_search
data.wa.gov.au	CKAN	https://catalogue.data.wa.gov.au/api/3/action/package_search
SEED	CKAN	https://datasets.seed.nsw.gov.au/api/3/action/package_search
CeRDI	CKAN	http://data2.cerdi.edu.au/api/3/action/package_search
AURIN	CKAN	https://data.aurin.org.au/api/3/action/package_search
AuScope	CKAN	https://geoanalytics.it.csiro.au/jdlc-geochem/api/3/action/package_search
Visualising Ballarat	CKAN	http://data.visualisingballarat.org.au/api/3/action/package_search
data.gov.au	Magda	https://data.gov.au/api/v0/search/datasets
CSIRO	OpenAPI	https://data.csiro.au/dap/ws/v2/
ARDC	getRIFCS (used), also OAI-PMH and other APIs	https://researchdata.ands.org.au/registry/services/5b4a0666b522/getRIFCS
Figshare	OpenAPI	https://api.figshare.com/v2
MLA	REST API	http://statistics.mla.com.au/ReportApi/

The FAIR metrics collection used during the FAIR evaluation in Chapter 5 is available at: https://fairsharing.github.io/FAIR-Evaluator-FrontEnd/#!/collections/15 and can be re-used for further testing.

A listing of the 18 Maturity Indicator Tests included in this collection:

- FAIR Metrics Gen2- Unique Identifier (F1): Metric to test if the metadata resource has a unique identifier. This is done by comparing the GUID to the patterns (by regexp) of known GUID schemas such as URLs and DOIs. Known schema are registered in FAIRSharing (https://fairsharing.org/standards/?q=&selected_facets=type_exact:identifier%20schema)
- FAIR Metrics Gen2 - Identifier Persistence (F1): Metric to test if the unique identifier of the metadata resource is likely to be persistent. Known schema are registered in FAIRSharing (https://fairsharing.org/standards/?q=&selected_facets=type_exact:identifier%20schema). For URLs that don't follow a schema in FAIRSharing we test known URL persistence schemas (purl, oclc, fdlp, purlz, w3id, ark).
- FAIR Metrics Gen2 - Data Identifier Persistence (F1): Metric to test if the unique identifier of the data resource is likely to be persistent. Known schema are registered

in FAIRSharing (https://fairsharing.org/standards/?q=&selected_facets=type_exact:identifier%20schema). For URLs that don't follow a schema in FAIRSharing we test known URL persistence schemas (purl, oclc, fdlp, purlz, w3id, ark).

- FAIR Metrics Gen2 - Structured Metadata (F2): Tests whether a machine is able to find structured metadata. This could be (for example) RDFa, embedded json, json-ld, or content-negotiated structured metadata such as RDF Turtle
- FAIR Metrics Gen2 - Grounded Metadata (F2): Tests whether a machine is able to find 'grounded' metadata. i.e. metadata terms that are in a resolvable namespace, where resolution leads to a definition of the meaning of the term. Examples include JSON-LD, embedded schema, or any form of RDF. This test currently excludes XML, even when terms are namespaced. Future versions of this test may be more flexible.
- FAIR Metrics Gen2 - Data Identifier Explicitly In Metadata (F3): Metric to test if the metadata contains the unique identifier to the data. This is done by searching for a variety of properties, including foaf:primaryTopic, schema:mainEntity, schema:distribution, sio:is-about, and iao:is-about. schema codeRepository is used for software releases.
- FAIR Metrics Gen2- Metadata Identifier Explicitly In Metadata (F3): Metric to test if the metadata contains the unique identifier to the metadata itself. This is done using a variety of 'scraping' tools, including DOI metadata resolution, the use of the 'extruct' Python tool, and others...
- FAIR Metrics Gen2 - Searchable in major search engine (F4): Tests whether a machine is able to discover the resource by search, using Microsoft Bing
- FAIR Metrics Gen2 - Uses open free protocol for data retrieval (A1.1): Data may be retrieved by an open and free protocol. Tests data GUID for its resolution protocol. Currently passes InChI Keys, DOIs, Handles, and URLs. Recognition of other identifiers will be added upon request by the community.
- FAIR Metrics Gen2 - Uses open free protocol for metadata retrieval (A1.1): Metadata may be retrieved by an open and free protocol. Tests metadata GUID for its resolution protocol. Currently passes InChI Keys, DOIs, Handles, and URLs. Recognition of other identifiers will be added upon request by the community.
- FAIR Metrics Gen2 - Data authentication and authorization (A1.2): Test a discovered data GUID for the ability to implement authentication and authorization in its resolution protocol. Currently passes InChI Keys, DOIs, Handles, and URLs. It also searches the metadata for the Dublin Core 'accessRights' property, which may point to a document describing the data access process. Recognition of other identifiers will be added upon request by the community.
- FAIR Metrics Gen2 - Metadata authentication and authorization (A1.2): Tests metadata GUID for the ability to implement authentication and authorization in its

resolution protocol. Currently passes InChI Keys, DOIs, Handles, and URLs. Recognition of other identifiers will be added upon request by the community.

- FAIR Metrics Gen2 - Metadata Persistence (A2): Metric to test if the metadata contains a persistence policy, explicitly identified by a persistencePolicy key (in hashed data) or a http://www.w3.org/2000/10/swap/pim/doc#persistencePolicy predicate in Linked Data.
- FAIR Metrics Gen2 - Metadata Knowledge Representation Language (weak) (I1): Maturity Indicator to test if the metadata uses a formal language broadly applicable for knowledge representation. This particular test takes a broad view of what defines a 'knowledge representation language'; in this evaluation, anything that can be represented as structured data will be accepted
- FAIR Metrics Gen2 - Data Knowledge Representation Language (weak) (I1): Maturity Indicator to test if the data uses a formal language broadly applicable for knowledge representation. This particular test takes a broad view of what defines a 'knowledge representation language'; in this evaluation, a knowledge representation language is interpreted as one in which terms are semantically-grounded in ontologies. Any form of structured data will pass this test
- FAIR Metrics Gen2 - Metadata uses FAIR vocabularies (weak) (I2): Maturity Indicator to test if the linked data metadata uses terms that resolve. This tests only if they resolve, not if they resolve to FAIR data, therefore is a somewhat weak test.
- FAIR Metrics Gen2 - Metadata contains qualified outward references) (I3): Maturity Indicator to test if the metadata links outward to third-party resources. It only tests metadata that can be represented as Linked Data.
- FAIR Metrics Gen2 - Metadata Includes License (weak) (R1.1): Maturity Indicator to test if the metadata contains an explicit pointer to the license. This 'weak' test will use a case-insensitive regular expression, and scan both key/value style metadata, as well as linked data metadata. Tests: xhtml, dvia, dcterms, cc, data.gov.au, and Schema license predicates in linked data, and validates the value of those properties
.

Appendix 2

This appendix contains information related to the livestock welfare case study in Chapter 5.

Table 5.5 - Data catalogues accessed in search

Organisation	Catalog/repository	URL
Government	Australian Government - data.gov.au	https://data.gov.au/
Government	Australian Government's Bureau of Meteorology (BOM)	http://www.bom.gov.au/climate/data/
Government	Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES)	https://www.agriculture.gov.au/abares
Government	Australian Bureau of Statistics (ABS)	https://www.abs.gov.au/Agriculture
Government	DataVic - State Government of Victoria	https://www.data.vic.gov.au/
Government	Tasmanian Government - theLIST	https://data.thelist.tas.gov.au/
Government	New South Wales Government - Data.NSW	https://data.nsw.gov.au/
Government	NSW Government SEED Sharing and Enabling Environmental Data	https://www.seed.nsw.gov.au/
Government	Government of Western Australia - data.wa.gov.au	https://www.data.wa.gov.au/
Government	Queensland Government - Open Data Portal	https://www.data.qld.gov.au/
Government	Northern Territory Government - data.nt.gov.au	https://data.nt.gov.au/
Government	Data.SA - South Australian Government Data Directory	https://data.sa.gov.au/
Government	Australian Capital Territory Government Open Data Portal - dataACT	https://www.data.act.gov.au/
Research	Commonwealth Scientific and Industrial Research Organisation (CSIRO) - Data Access Portal	https://data.csiro.au/dap/home?execution=e1s1
Research	National Collaborative Research Infrastructure Strategy (NCRIS) AuScope	https://www.auscope.org.au/
Research	Research Data Australia	https://researchdata.ands.org.au/
Research	CeRDI Federation University Australia FedUni research data catalogue	http://data2.cerdi.edu.au/
Research	Atlas of Living Australia (ALA)	https://www.ala.org.au/
Industry	Meat & Livestock Australia (MLA)	https://www.mla.com.au/
Research	Figshare	https://figshare.com/
Research	Dryad	https://datadryad.org/search
Research	Zenodo	https://zenodo.org/
Other	Google Dataset Search	https://datasetsearch.research.google.com/

Name	URL
Australian Government, Department of Agriculture, Water and the Environment: Animal pests and diseases	https://www.agriculture.gov.au/pests-diseases-weeds/animal
Animal Health Australia	https://www.animalhealthaustralia.com.au/
Farm Biosecurity	https://www.farmbiosecurity.com.au/
Commonwealth of Australia: National pest & disease outbreaks	https://www.outbreak.gov.au/pests-and-diseases
World Organisation for Animal Health (OIE): Information on aquatic and terrestrial animal diseases	https://www.oie.int/en/animal-health-in-the-world/information-on-aquatic-and-terrestrial-animal-diseases/
Meat & Livestock Australia: Animal health & welfare	https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/
Meat & Livestock Australia: The cattle parasite atlas	https://publications.mla.com.au/login/eaccess?elink=rnS6UxS0cYs3sn95fjSm
Meat & Livestock Australia: 6.07 - Cattle disease guide	https://mbfp.mla.com.au/herd-health-and-welfare/tool-6.07cattle-disease-guide/
Meat & Livestock Australia: Toxic plants	https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/poisonings/toxic-plants/
Australian Government, Department of Agriculture, Water and the Environment: Animal product residue monitoring	https://www.agriculture.gov.au/ag-farm-food/food/nrs/animal-residue-monitoring
Meat & Livestock Australia: Mineral deficiencies	https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/nutritional/mineral-deficiencies/
Centre for Agriculture and Bioscience International (CABI): Invasive Species Compendium	https://www.cabi.org/isc/
MSD Veterinary Manual	https://www.msdvetmanual.com/

Table 5.6 - Cattle conditions

Name	Alt. name	caused by	geographic factor	weather factors	included	searched	pasture factors	animal class	related to	information from	Other notes
Tetanus		Clostridium (bacterium)	no		n					https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/infectious/clostridial-diseases/	
Black disease	Infectious Necrotic Hepatitis	Clostridium	no		n				Liver fluke	https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/infectious/clostridial-diseases/	
Black leg		Clostridium	no		n					https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/infectious/clostridial-diseases/	
Malignant oedema		Clostridium	no		n					https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/infectious/clostridial-diseases/	
Pulpy kidney		Clostridium	no		n		lush pastures			https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/infectious/clostridial-diseases/	
Botulism		Clostridium	no		n		lack of good pasture	zoonotic	P deficiency (animals chew bones which leads to infection)	https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/infectious/clostridial-diseases/	
Calf scours		combination	no		n			calves young	Cu, Se deficiency	https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/infectious/calf-scours/	
Grass tetany		hypomagnesemia	place with prior history	cold/ wet	n		short or not enough roughage	lactating or in oestrus	Mg deficiency	https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/nutritional/grass-tetany/	

Name	Alt. name	caused by	geographic factor	weather factors	included	searched	pasture factors	animal class	related to	information from	Other notes
Ketosis	Pregnancy Toxaemia	lack of feed	no	cold/ wet	n		lack of pasture	lactation early		https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/nutritional/pregnancy-toxaemia/	
Leptospirosis		Leptospira (bacterium)	place with prior history	hot/humid climate	y	not found		zoonotic, pregnant cows, calves		https://www.agriculture.gov.au/sites/default/files/sitecollectiondocuments/ba/animal/horsesubmissions/leptoreviewfinal.pdf	https://www.cabi.org/isc/datasheet/77199
Milk fever	Hypocalcaemia	hypocalcaemia	place with prior history		n		grass-dominant	pregnancy late	Ca deficiency	https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/nutritional/milk-fever/	
Muscosal disease		Bovine Viral Diarrhoea (BVDV)	no	no	n			young stock	BVDV	https://www.agric.wa.gov.au/livestock-biosecurity/bovine-pestivirus-or-bovine-viral-diarrhoea-virus-bvdv-and-mucosal-disease	
Pinkeye		bacteria (various)	no	dry/ dusty	n		grass seeds			https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/infectious/pinkeye/	
Trichomoniasis		Tritrichomonas (protozoa parasite)	Northern Australia		y	not found		breeding cattle	parasites	https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/reproductive/trichomoniasis/	
Vibriosis		Campylobacter fetus (bacterium)	no		n					https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/reproductive/vibriosis/	
Bovine ephemeral fever	Three day sickness, BEFV	arbovirus	northern Australia and along the eastern seaboard south to the NSW-VIC border	after big wet season	y	not found		young stock, relatively benign, more problem in other species	mosquitoes	https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/infectious/three-day-sickness/	

Name	Alt. name	caused by	geographic factor	weather factors	included	searched	pasture factors	animal class	related to	information from	Other notes
Bluetongue	BTV	arbovirus	specific zone, tropical to sub-tropical latitudes		y	found			haematophagous arthropods, biting midges, predominantly Culicoides	https://www.animalhealthaustralia.com.au/what-we-do/disease-surveillance/national-arbovirus-monitoring-program/	
Akabane virus	AKAV	arbovirus	not present		n				haematophagous arthropods	https://journals.plos.org/plosntds/article?id=10.1371/journal.pntd.0003325	
Bloat – pasture related		feed	no		n		clover-dominant			https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/nutritional/bloat/	
Pestivirus	Bovine Viral Diarrhoea (BVDV)	Pestivirus	no	no	n					https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/reproductive/pestivirus/	
Anthrax		Bacillus anthracis	anthrax belt	hot/dry	y	Un-available				https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/infectious/anthrax/	
Brucellosis		Brucella abortus	not present		n			breeding stock		https://www.dpi.nsw.gov.au/about-us/services/laboratory-services/veterinary/brucellosis-cattle	
Johne's disease	BJD	Mycobacterium avium (bacterium)	not WA		y	not found				https://www.animalhealthaustralia.com.au/what-we-do/endemic-disease/johnes-disease-in-cattle/spread-and-prevalence/	notifiable disease, uncommon in beef cattle, less likely in northern and western Australia. National BJD Strategic Plan 2012-2020 had zoning, but now run by

Name	Alt. name	caused by	geographic factor	weather factors	included	searched	pasture factors	animal class	related to	information from	Other notes
											the BJD in Cattle Framework, zones have been removed.
Chagas Disease		Trypanosoma cruzi	not present		n						
Infectious bovine rhinotracheitis	IBR	herpes virus	only benign strain in Australia		n					https://www.agriculture.gov.au/sites/default/files/sitecollectiondocuments/animal/ahl/ANZSDP-Infectious-bovine-rhinotracheitis-IBR.pdf	
Encephalitis (tick borne)			not present		n					https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6360175/	
Epizootic haemorrhagic disease			not present		n						
Australian bat lyssavirus			not present		n						
Borna disease			not present		n						
Crimean-Congo haemorrhagic fever			not present		n						
Infection with Echinococcus multilocularis			not present		n						
Heartwater			not present		n						
Foot and mouth disease			not present		n						
Tularaemia			not present		n						
Japanese encephalitis			not present		n						
Leishmaniasis			not present		n						

Name	Alt. name	caused by	geographic factor	weather factors	included	searched	pasture factors	animal class	related to	information from	Other notes
Infection with Mycobacterium			not present		n						
Tuberculosis			not present		n						
Rabies			not present		n						
Rift Valley fever			not present		n						
Rinderpest			not present		n						
Infection with Trichinella spp.			not present		n						
Surra			not present		n						
Seneca Valley virus			not present		n						
Old World Screwworm			not present		n						
New World screwworm			not present		n						
Warble-fly myiasis			not present		n						
Bovine spongiform encephalopathy			not present		n						
Trypanosomosis - tsetse fly associated			not present		n						
West Nile Virus			not present		n						
Haemorrhagic septicaemia		Pasteurella multocida, a coccobacillus	not present		n					https://www.oie.int/fileadmin/Home/eng/Animal_Health_in_the_World/docs/pdf/Disease_cards/HAEMORRHAGIC_SEPTICEMIA.pdf	

Name	Alt. name	caused by	geographic factor	weather factors	included	searched	pasture factors	animal class	related to	information from	Other notes
Bovine anaplasmosis		parasites: Anaplasma marginale and Anaplasma	in tick regions	high humidity and ambient temperatures of at least 15-20 deg.C	y	not found		Bos taurus more likely than B.indicus	presence of cattle ticks	https://www.agriculture.gov.au/sites/default/files/sitecollectiondocuments/animal/ahl/ANZSDP-Tick_borne_diseases.pdf	notifiable outside tick zone
bovine babesiosis		parasites: Babesia bovis, B. bigemina or B. divergens	in tick regions	high humidity and ambient temperatures of at least 15-20 deg.C	y	not found		Bos taurus more likely than B.indicus	presence of cattle ticks	https://www.agriculture.gov.au/sites/default/files/sitecollectiondocuments/animal/ahl/ANZSDP-Tick_borne_diseases.pdf	notifiable outside tick zone
Bovine leukaemia (enzootic bovine leucosis)	EBL	bovine leukaemia virus (BLV)	no		n			mature cattle		https://www.dpi.nsw.gov.au/about-us/services/laboratory-services/veterinary/enzootic-bovine-leukosis-cattle	
Jembrana disease		Lentivirus	not present		n					https://europepmc.org/article/med/8545963	
Louping ill		Flavivirus	not present		n			zoonotic	ticks	http://apha.defra.gov.uk/documents/surveillance/tick-borne-disease-presentation.pdf	
Lumpy skin disease	LSD	capripox virus	not present		n					https://agriculture.vic.gov.au/biosecurity/animal-diseases/beef-and-dairy-cattle/lumpy-skin-disease	
Contagious bovine pleuropneumonia		bacterium	not present		n					https://csiropedia.csiro.au/contagious-bovine-pleuropneumonia-eradication/	
Cysticercus bovis		Taenia saginata	no		n					https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0010/432892/cysticercus-bovis-in-cattle.pdf	
Upper alimentary ulcerative syndrome	UAUS	unidentified	Victoria		y	not found		weaned calves		https://agriculture.vic.gov.au/biosecurity/animal-diseases/beef-and-dairy-cattle/upper-alimentary-ulcerative-syndrome	

Name	Alt. name	caused by	geographic factor	weather factors	included	searched	pasture factors	animal class	related to	information from	Other notes
Theileriosis		Theileria orientalis	coastal regions of New South Wales, Victoria and Queensland, detected in all states and territories except Tasmania		y	not found		young, pregnant or post calving	ticks of the genus Haemap hysalis Bush tick – H longicornis, and Wallaby tick – H bancrofti	https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/parasites/identification/theileriosis/	
Australian cattle tick		Rhipicephalus australis	designated tick zone	high humidity, temperatures of at least 15–20°C	y	found				https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/parasites/identification/ticks/	
Cattle tick		Rhipicephalus microplus	designated tick zone	high humidity, temperatures of at least 15–20°C	y	found				https://www.animalhealthaustralia.com.au/wp-content/uploads/2015/09/AHIA2015_Chapter2.pdf	
Paralysis tick		Ixodes holocyclus, I. cornuatus	coastal areas of eastern Australia		y	found	scrubby, overgrown	calves also other species		https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/parasites/identification/ticks/	
Bush tick		Haemaphysalis longicornis	east coast of Australia		y	found		other species	transmits Theileria	https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/parasites/identification/ticks/	
Buffalo fly		Siphona exigua	yes, northern parts	hot and humid	y	not found		dark coats, older, poor condition		https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/parasites/identification/flies/	
Barber's pole worm		Haemonchus placei		over 500-600 mm annual rainfall, hot and humid	y	not found	irrigated	youngstock, stressed, calving, bulls		https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/parasites/identification/gastrointestinal-worms/	
Biting louse		Bovicola bovis	no	winter	n					https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/parasites/identification/lice/	

Name	Alt. name	caused by	geographic factor	weather factors	included	searched	pasture factors	animal class	related to	information from	Other notes
Black scours	Black scour worm	Eimeria spp.	no	cold and wet, winter rainfall zones 500-600 mm annual rainfall	y	not found		youngstock, stressed, calving, bulls		https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/parasites/identification/gastrointestinal-worms/	
Coccidia	Post weaning diarrhea (PWD)	Eimeria bovis and E. zuernii	no	warm + wet	y	not found		youngstock, poor condition, stressed		https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/parasites/identification/coccidiosis/	
Large stomach worm		Haemonchus placei	no	high rainfall regions with more than 500-600 mm annual rainfall	y	not found	irrigated			https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/parasites/identification/gastrointestinal-worms/	
Liver fluke	Fascioliasis	Fasciola hepatica	All states other than WA	higher rainfall (>600 mm per year)	y	not found	wet or near watercourses		certain types of snails	http://www.wormboss.com.au/sheep-goats/worms/flukes/liver-fluke.php	
Long-nosed sucking louse		Linognathus vituli	no	winter	n					https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/parasites/identification/lice/	
Paramphistomes	Stomach fluke	Calicophoron calliphorum	Light infections, due to adult and immature flukes, occur on the Southern and Central Tablelands, the Slopes, and in coastal areas.		y	not found	wet or near watercourses, presence of planorbit snails	weaners	Planorbid snails must be present	https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0006/110103/stomach-fluke-paramphistomes-in-ruminants.pdf	

Name	Alt. name	caused by	geographic factor	weather factors	included	searched	pasture factors	animal class	related to	information from	Other notes
			Serious outbreaks from heavy infections with immature flukes may occur on the New England Tablelands, the North and South Coast, and in irrigation areas.								
Short-nosed sucking louse		Haematopinus eurysternus	no	high rainfall regions with more than 500-600 mm annual rainfall	y		irrigated	youngstock, stressed, calving, bulls		https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/parasites/identification/gastrointestinal-worms/	
Long-nosed sucking louse		Linognathus vituli			n					no information found	
Small brown stomach worm		Ostertagia ostertagi	no	cold and wet, winter rainfall zones 500-600 mm annual rainfall	y		irrigated	youngstock, stressed, calving, bulls		https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/parasites/identification/gastrointestinal-worms/	
Small intestinal worm		Cooperia punctata	no	high rainfall regions with more than 500-600 mm annual rainfall	y		irrigated	youngstock, stressed, calving, bulls		https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/parasites/identification/gastrointestinal-worms/	

Name	Alt. name	caused by	geographic factor	weather factors	included	searched	pasture factors	animal class	related to	information from	Other notes
Stomach hair worm			no	high rainfall regions with more than 500-600 mm annual rainfall	y		irrigated	youngstock, stressed, calving, bulls		https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/parasites/identification/gastrointestinal-worms/	
Copper deficiency		soil deficiency	coastal sandy soils, granite, peat swamps		y	not found		breeding & young stock	excess Mo	https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/nutritional/mineral-deficiencies/	
Selenium deficiency		soil deficiency	coastal sandy soils, acidic soils, sedimentary and granite soils	high rainfall	y	not found	clover-dominant	young stock		https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/nutritional/mineral-deficiencies/	
Cobalt deficiency		soil deficiency	coastal calcareous sands, high rainfall granite soils and krasnozem soils		y	not found		young stock		https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/nutritional/mineral-deficiencies/	
Phosphorous deficiency		soil deficiency	phosphorous deficient soil	spring	y	not found	lush	young stock		https://www.mla.com.au/research-and-development/animal-health-welfare-and-biosecurity/diseases/nutritional/mineral-deficiencies/	

Table 5.7 - Welfare layers

Topic	Name	Scope	in QGIS	Resolution	Currency	Source	Type	URL	Licence	Notes	Citation
Weather	Annual and monthly potential frost days - annual - less than 2 degrees	national	no	5km		BOM	TXT (grid)	http://www.bom.gov.au/jsp/ncc/climate_averages/frost/	http://creativecommons.org/licenses/by/3.0/au/		
	Annual and monthly potential frost days - annual - less than 0 degrees	national	no	5km		BOM	TXT (grid)	http://www.bom.gov.au/jsp/ncc/climate_averages/frost/	http://creativecommons.org/licenses/by/3.0/au/		
	Annual and monthly potential frost days - annual - less than -2 degrees	national	no	5km		BOM	TXT (grid)	http://www.bom.gov.au/jsp/ncc/climate_averages/frost/	http://creativecommons.org/licenses/by/3.0/au/		
	Annual and monthly potential frost days - annual - less than -5 degrees	national	no	5km		BOM	TXT (grid)	http://www.bom.gov.au/jsp/ncc/climate_averages/frost/	http://creativecommons.org/licenses/by/3.0/au/		
	Climate zones based on temperature and humidity	national	no	2.5km		BOM	TXT (grid)	http://www.bom.gov.au/jsp/ncc/climate_averages/climate-classifications/	http://creativecommons.org/licenses/by/3.0/au/		
	Climate classification of Australia (Koeppen - all classes)	national	yes	2.5km		BOM	TXT (grid)	http://www.bom.gov.au/jsp/ncc/climate_averages/climate-classifications/	http://creativecommons.org/licenses/by/3.0/au/	clipped and converted to shape file	
	Seasonal rainfall zones (all zones)	national	yes	25km		BOM	TXT (grid)	http://www.bom.gov.au/jsp/ncc/climate_averages/climate-classifications/	http://creativecommons.org/licenses/by/3.0/au/	clipped and converted to shape file	Australian Government Bureau of Meteorology. (2016). Seasonal rainfall - all zones. Retrieved from: http://www.bom.gov.au/jsp/ncc/climate_averages/climat

Topic	Name	Scope	in QGIS	Resolution	Currency	Source	Type	URL	Licence	Notes	Citation
											e-classifications/index.jsp?maptype=seasb#maps. Accessed 3 October 2020
	NDVI - monthly	national	no	25km	monthly	BOM	TXT (grid)	http://www.bom.gov.au/jsp/awap/ndvi/index.jsp	http://creativecommons.org/licenses/by/3.0/au/		
	Temperatures (daily to annually, max, min, mean, deciles)	national	no	5km	daily	BOM	TXT (grid)	http://www.bom.gov.au/jsp/awap/temp/index.jsp	http://creativecommons.org/licenses/by/3.0/au/		
	Temperatures max, min, mean (averages annual or by month)	national	no	2.5km		BOM	TXT (grid)		http://creativecommons.org/licenses/by/3.0/au/		
	Annual rainfall	national	no			BOM	WMS/WFS	via CeRDI geoserver		clipped, based on BOM data	http://geo.cerdi.com.au/geoserver/vas
Natural disasters	NSW Bush Fire Prone Land	NSW	yes	vector	9-Oct-20	NSW RFS	SHP	https://portal.spatial.nsw.gov.au/portal/home/item.html?id=3de03ae1965840cfa5dcd9e4018745a7	https://creativecommons.org/licenses/by/4.0/		NSW Rural Fires Service. (2020). NSW Bush Fire Prone Land. Retrieved from: https://portal.spatial.nsw.gov.au/portal/home/item.html?id=3de03ae1965840cfa5dcd9e4018745a7. Accessed 6 November 2020
	NSW Flood Data Portal	NSW	no			NSW SES	various	https://flooddata.ses.nsw.gov.au/related-dataset/	various	2438 supplied by various orgs, many in unsuitable format	

Topic	Name	Scope	in QGIS	Resolution	Currency	Source	Type	URL	Licence	Notes	Citation
	Soil landscape land quality - Flood Risk (DPIRD 007)	WA	yes	vector		DPIRD	WMS/WFS	https://catalogue.data.wa.gov.au/dataset/soil-landscape-mapping-rangelands	https://creativecommons.org/licenses/by/4.0/		Government of Western Australia Department of Primary Industries and Regional Development. (2018). Soil Landscape Mapping - Rangelands (DPIRD-063). Retrieved from: https://catalogue.data.wa.gov.au/dataset/soil-landscape-mapping-rangelands. Accessed 5 November 2020
	Agricultural land audit - frequency of 75kmph cyclonic wind gusts - Queensland	QLD	yes		2014	QLD Spatial	SHP	http://qldspatial.information.qld.gov.au/catalogue/custom/detail.page?fid={B5CD0878-AE5D-4C12-ADFC-B12D17890CE9}			Queensland Department of Agriculture and Fisheries. (2014). Agricultural land audit - frequency of 75kmph cyclonic wind gusts - Queensland. Retrieved from: http://qldspatial.information.qld.gov.au/catalogue/custom/detail.page?fid=(Queensland Department of Agriculture and

Topic	Name	Scope	in QGIS	Resolution	Currency	Source	Type	URL	Licence	Notes	Citation
											Fisheries). Accessed 19 October 2020
	Agricultural land audit - frequency of 150kmph cyclonic wind gusts - Queensland	QLD	yes		2014	QLD Spatial	SHP	Agricultural land audit - frequency of 150kmph cyclonic wind gusts - Queensland			Queensland Department of Agriculture and Fisheries. (2014). Agricultural land audit - frequency of 150kmph cyclonic wind gusts - Queensland. Retrieved from: http://qldspatial.information.qld.gov.au/catalogue/custom/detail.page?fid=(Queensland Department of Agriculture and Fisheries). Accessed 19 October 2020
	Flammability	National	no	grid	2020	Australian Flammability Monitoring System	TIFF	http://wenfo.org/afms/			

Topic	Name	Scope	in QGIS	Resolution	Currency	Source	Type	URL	Licence	Notes	Citation
	Live Fuel Moisture Content	National	no	grid	2020	Australian Flammability Monitoring System	TIFF	http://wenfo.org/afms/			
Water	Victorian Farm Dam Boundaries	VIC	yes	vector	2016		SHP	https://data.gov.au/dataset/ds-dga-abdca916-8362-456e-aa36-7a3a852d0aa0/distribution/dist-dga-7b7ede81-a73c-4a69-85ea-516273929863/details?q=farm%20dam	http://creativecommons.org/licenses/by/3.0/au/		
	Dams of the Bioregional Assessment subregions	national	yes	vector	2016		SHP	https://data.gov.au/dataset/ds-dga-6e420f31-08b1-44bb-ac61-cd4dcdb70dce/details?q=farm%20dam	http://creativecommons.org/licenses/by/4.0/		
	State Environmental Planning Policy No 52-Farm Dams and Other Works in Land and Water Management Plan Areas	NSW	no	vector			ESRI REST	https://data.nsw.gov.au/data/dataset/16e80b0a-15d9-4207-b241-7f4aa5f6f949		loads zero features	
	Surface_HydroPolys_National	national	no	vector			ArcGIS Feature Service				

Topic	Name	Scope	in QGIS	Resolution	Currency	Source	Type	URL	Licence	Notes	Citation
	Geofabric OGC Web Services	national	no				WMS/WFS or ArcGIS	http://geofabric.bom.gov.au/documentation/	http://creativecommons.org/licenses/by/3.0/au/	Guide at: http://www.bom.gov.au/water/geofabric/documents/geofabric_web_services_user_guide.pdf	
	Australian Groundwater Explorer (NSW set)	national (available by state)	no	vector		BOM	SHP	http://www.bom.gov.au/water/groundwater/explorer/map.shtml	http://creativecommons.org/licenses/by/3.0/au/	more info at: http://www.bom.gov.au/water/about/publications/document/InfoSheet_19.pdf	
	Farm dams of the South West agricultural region of WA (DPIRD-083)	WA	no	vector	2020	DPIRD	WMS/WFS	https://data.gov.au/dataset/ds-wa-ce2e03b6-9188-4c2e-ae5c-2cc71b5f6c84/details?q=farm%20dam			
Feed	Stock routes - Queensland	QLD	Yes	vector	2020	QLD Spatial	SHP, TAB, FGDB, KMZ, GPKG	http://qldspatial.information.qld.gov.au/catalogue/custom/search.page?q=%22Stock%20routes%20-%20Queensland%22	http://creativecommons.org/licenses/by/4.0/		State of Queensland (Department of Natural Resources, Mines and Energy). (2013). Stock routes - Queensland. Retrieved from:

Topic	Name	Scope	in QGIS	Resolution	Currency	Source	Type	URL	Licence	Notes	Citation
											http://qldspatial.information.qld.gov.au/catalogue/custom/search.page?q=%22Stock%20routes%20-%20Queensland%22. Accessed 15 November 2020
	Conservation value of NSW Travelling Stock Reserves (TSRs)	NSW	Yes	vector	2020	SEED	GEODATABASE	https://datasets.seed.nsw.gov.au/dataset/travelling-stock-reserves	https://creativecommons.org/licenses/by/4.0/		Department of Regional New South Wales. (2020). Conservation value of NSW Travelling Stock Reserves (TSRs). Retrieved from: https://datasets.seed.nsw.gov.au/dataset/travelling-stock-reserves. Accessed 15 November 2020
	TSR Conservation Values	NSW	No	vector	2010	NSW Department of Environment,Climate Change and Water	SHP	https://data.gov.au/data/dataset/8d55e731-8702-4b56-b7b8-e1f635f46329	http://creativecommons.org/licenses/by/3.0/au/		
	Soil Landscape Mapping - Rangelands (DPIRD-063)	WA	yes	vector	2019	DPIRD	WMS, WFS, other	https://catalogue.data.wa.gov.au/dataset/soil-landscape-mapping-rangelands	https://creativecommons.org/licenses/by/4.0/		

Topic	Name	Scope	in QGIS	Resolution	Currency	Source	Type	URL	Licence	Notes	Citation
Parasites	Animal biosecurity zones - Queensland series	QLD	Yes	vector	2016	QLD Spatial	SHP	http://qldspatial.information.qld.gov.au/catalogue/custom/detail.page?fid={E4B9B2D7-C0CC-4E9E-94EE-3F78758C20FE}			
	Cattle tick line QLD 2018	QLD	no	vector	2018	State of Queensland (Department of Agriculture and Fisheries)	ArcGIS Feature Service	https://services1.arcgis.com/HrMiNYsSqqPpLTDE/arcgis/rest/services/TickLineWeb2018/FeatureServer		unable to access	© State of Queensland (Department of Agriculture and Fisheries), 2018
	Cattle tick zones - Queensland	QLD	yes	vector	2016	QLD Spatial	SHP	http://qldspatial.information.qld.gov.au/catalogue/custom/detail.page?fid={142D5849-A68F-4E74-A14A-0936F32050C4}			Biosecurity Queensland. (2016). Cattle tick zones - Queensland. Retrieved from: http://qldspatial.information.qld.gov.au/catalogue/custom/detail.page?fid={142D5849-A68F-4E74-A14A-0936F32050C4}. Accessed 2 November 2020
	Cattle tick clearing facilities - locations for 2014-15	QLD	No	vector	2019	data.qld.gov.au	CSV	https://www.data.qld.gov.au/dataset/cattle-tick-clearing-facilities-locations/resource/21e943ab-2f80-4b9f-8fdd-987e11497658			

Topic	Name	Scope	in QGIS	Resolution	Currency	Source	Type	URL	Licence	Notes	Citation
	Northern Territory Tick Areas	NT	no				PDF	https://nt.gov.au/__data/assets/pdf_file/0016/205306/map-of-NT-cattle-tick-areas.pdf		only available as PDF	
	Cattle Tick Infected Area of WA	WA	no			DPIRD		https://www.agric.wa.gov.au/livestock-biosecurity/conditions-entry-stock-relation-tick-western-australia		only available as image/pdf	
	Paralysis tick - Ixodes holocyclus & I. cornuatus	national	yes	point	2020	ALA	CSV	https://doi.org/10.26197/ala.71d7ca4c-af5e-49d9-b1a4-e802affae4ac	Creative Commons Attribution (CC-BY) 4.0 License		Atlas of Living Australia occurrence download at https://biocache.ala.org.au/occurrences/search?q=qid%3A1605676622393 accessed on 18 November 2020.
	Australian cattle tick - Boophilus microplus	national	no	point		ALA				only 12 records, very old or invalid collection dates noted	
	Bush tick - Haemaphysalis longicornis	national	yes	point		ALA			Creative Commons Attribution (CC-BY) 4.0 License		Atlas of Living Australia occurrence download at https://biocache.ala.org.au/occurrences/search?q=lsid%3Aurn%3Alsid%3Abiodiversity.org.au%3Aafd.taxon%3Ad29

Topic	Name	Scope	in QGIS	Resolution	Currency	Source	Type	URL	Licence	Notes	Citation
											02d0e-d193-49ae-8973-473ca4e383ba accessed on 18 November 2020.
Diseases	Bluetongue Virus	national	Yes	vector	2020	Animal Health Australia	SHP	https://namp.animalhealthaustralia.com.au/public.php?page=pub_home&program=2			
Deficiencies, Soils	Soil and Landscape Grid National Soil Attribute Maps - Total Phosphorus (3" resolution) - Release 1	national	No	3" (90 x 90m)	2018	CSIRO	WMS, WCS, TIFF	https://doi.org/10.4225/08/546F617719CAF	https://creativecommons.org/licenses/by/4.0/		https://doi-org.ezproxy.federation.edu.au/10.1016/j.scitotenv.2015.09.119
	Geochemical map of Australia (First Edition) - Se (selenium) series	national	No		2011	GA	PDF	http://pid.geoscience.gov.au/dataset/ga/71908	Creative Commons Attribution 4.0 International Licence		de Caritat, P., Cooper, M. 2011. Geochemical map of Australia (First Edition) - Se (selenium) series. Geoscience Australia, Canberra. http://pid.geoscience.gov.au/dataset/ga/71908
	Digital soil maps for key soil properties over New South Wales, version 1.2	NSW	yes	100m	2019	NSW Planning & Enviroment	ArcGrid	https://datasets.seed.nsw.gov.au/dataset/digital-soil-maps-for-key-soil-properties-over-nsw	https://creativecommons.org/licenses/by/4.0/		

Topic	Name	Scope	in QGIS	Resolution	Currency	Source	Type	URL	Licence	Notes	Citation
Toxins	St Johns Wort	national	yes	point	2020	ALA	CSV	https://doi.org/10.26197/ala.3026d639-524f-4f62-b44b-5bc90f6b45f1	Creative Commons Attribution (CC-BY) 4.0 License		
	Pimelea	national	yes	point	2020	ALA	CSV	https://doi.org/10.26197/ala.8b74b539-0641-4b4f-8bc8-1d5c57a60c2b	Creative Commons Attribution (CC-BY) 4.0 License		
	Patersons Curse	national	yes	point	2020	ALA	CSV	https://doi.org/10.26197/ala.cbeb4c53-18a5-46fe-a621-4deff49ae96a	Creative Commons Attribution (CC-BY) 4.0 License		
	Nightshade	national	yes	point	2020	ALA	CSV	https://doi.org/10.26197/ala.2a910fa6-28bc-450a-b656-b9d545792fc3	Creative Commons Attribution (CC-BY) 4.0 License		
	Larkspur	national	yes	point	2020	ALA	CSV	https://doi.org/10.26197/ala.8d23a0ef-b69c-4cb8-afba-3a8e4f94b10f	Creative Commons Attribution (CC-BY) 4.0 License		
	Hemlock	national	yes	point	2020	ALA	CSV	https://doi.org/10.26197/ala.62943672-58a0-4ed2-8e64-386c99bdfa60	Creative Commons Attribution (CC-BY) 4.0 License		
	Ryegrass	national	yes	point	2020	ALA	CSV	https://doi.org/10.26197/ala.692256ec-e753-4486-8d3d-b0392557b2fb	Creative Commons Attribution (CC-BY) 4.0 License		
	NSW Contaminated sites	NSW	yes	point	2020	EPA NSW	EXCEL	https://www.epa.nsw.gov.au/your-environment/contaminated-land/notified-and-regulated-contaminated-land/list-of-notified-sites			

Topic	Name	Scope	in QGIS	Resolution	Currency	Source	Type	URL	Licence	Notes	Citation
	Victorian Landfill Register (VLR)	VIC	yes	point	2020	EPA VIC	CSV	https://www.epa.vic.gov.au/for-community/environmental-information/waste/landfills/victorian-landfill-register#accessing-the-register			
Predators	State Barrier Fence (DPIRD-025)	WA	yes	vector		DPIRD	ArcGIS Map Service	https://services.slip.wa.gov.au/public/rest/services/SLIP_Public_Services/Buildings_and_Structures/MapServer			Department of Agriculture and Food, Western Australia. State Barrier Fence (DPIRD-025). Retrieved from: https://services.slip.wa.gov.au/public/rest/services/SLIP_Public_Services/Buildings_and_Structures/MapServer/0. Accessed 12 October 2020
	Queensland wild dog barrier and check fences 2016	QLD	yes	vector	2016	QLD Spatial	SHP	http://qldspatial.information.qld.gov.au/catalogue/custom/detail.page?fid={14E8AEDE-7EC5-445B-9FDE-31B7FF2025DA}			Queensland Department of Agriculture and Fisheries. (2016). Queensland wild dog barrier and check fences 2016. Retrieved from: http://qldspatial.information.qld.gov.au/catalogue/custom/detail.page?fid={

Topic	Name	Scope	in QGIS	Resolution	Currency	Source	Type	URL	Licence	Notes	Citation
											14E8AEDE-7EC5-445B-9FDE-31B7FF2025DA}. Accessed 17 October 2020
	Queensland rabbit fence 2016	QLD	no	vector	2016	QLD Spatial	SHP	http://qldspatial.information.qld.gov.au/catalogue/custom/detail.page?fid={5E9EC7FB-99EE-4B2A-A43D-81FA0E44578D}			
	Dingo Fence	national				OSM	GeoJSON	https://www.openstreetmap.org/relation/3776543		exported via Overpass API	OpenStreetMap contributors. (2020). Dingozaun dump. Retrieved from: https://www.openstreetmap.org/relation/3776543. Accessed 11 October 2020
	Invasive species - Vertebrate Animals - National Survey 2006 - Dataset - Flat database structure (7 columns)	national	yes	grid 1:100,000	2006	ABARES	SHP	https://data.agriculture.gov.au/geonetwork/srv/eng/catalog.search#/metadata/fb519f28-e3e7-4617-947d-170d6cba4841			Australian Bureau of Agricultural and Resource Economics. (2006). Invasive species - Vertebrate Animals - National Survey 2006 - Dataset - Flat database structure (7 columns). Retrieved from:

Topic	Name	Scope	in QGIS	Resolution	Currency	Source	Type	URL	Licence	Notes	Citation
											https://data.agriculture.gov.au/geonetwork/srv/eng/catalog.search#/metadata/fb519f28-e3e7-4617-947d-170d6cba4841. Accessed 11 October 2020

Table 5.8 - Supporting Layers

Topic	Name	Scope	Dated	Source	Type	URL
Boundaries	Australian Agricultural and Grazing Industries Survey (AAGIS) zones and regions	national	2016	ABARES	SHP	https://www.agriculture.gov.au/abares/research-topics/surveys/farm-survey-data
	NRM regions	national	2020	Department of Environment		https://www.environment.gov.au/fed/catalog/search/resource/details.page?uuid=%7BAB80DA43-CB00-455D-8A3C-70162EB8D964%7D
	Australia outline	national				
	Local Government Areas	national	2020	ABS	SHP	https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/1270.0.55.003June%202020?OpenDocument
	ABARES regions, farm survey statistical aggregation areas	national	2011	ABARES	SHP	https://data.agriculture.gov.au/geonetwork/srv/eng/catalog.search#/metadata/8855aba9-8ca9-48bb-9d0c-489b2beba681
Land use	Land use in Australia's Rangelands for 1996	national	2001	ABARES	SHP	https://data.agriculture.gov.au/geonetwork/srv/eng/catalog.search#/metadata/4cedee02-7ce7-4fae-baea-ab565b7085f6
	Catchment scale land use of Australia	national	2017	ABARES	SHP	https://data.agriculture.gov.au/geonetwork/srv/eng/catalog.search#/metadata/7f54d91e-0d24-4a7f-bd08-2fda09c95bce
	Various regional land use datasets	varies	varies	ABARES	SHP	https://data.agriculture.gov.au/geonetwork/srv/eng/catalog.search#/search?facet.q=keyword%2FAgriculture&resultType=details&sortBy=relevance&any=land%20use&fast=index&_content_type=json&from=1&to=20
Soil	Soil Landscape Mapping Rangelands - DPIRD 063	WA		DPIRD	WFS	https://services.slip.wa.gov.au/public/services/SLIP_Public_Services/Soil_Landscape_WFS/MapServer/WFSServer

Table 5.9 - Geospatial portals

Topic	Name	URL	Datasets available	Maintainer	Notes
Predators	Wild Dog Scan	https://www.feralscan.org.au/wilddogscan/map.aspx	NO	Centre for Invasive Species Solutions	Part of Feralscan
Natural Disasters	Australian Flammability Monitoring System	http://wenfo.org/afms/	YES	BUSHFIRE & NATURAL HAZARDS CRC	related publication at: https://www.bnhcrc.com.au/file/11828/download?token=jAG__Esi
	Digital Earth Australia Hotspots	https://hotspots.dea.ga.gov.au/		Geoscience Australia	
	Earthquakes@GA	https://earthquakes.ga.gov.au/		Geoscience Australia	
	Vic Emergency	http://emergency.vic.gov.au/respond/		State/Territory Government	
	CFS South Australia	https://apps.geohub.sa.gov.au/CFSMap/index.html		State/Territory Government	
	NSW RURAL FIRE SERVICE	https://www.rfs.nsw.gov.au/fire-information/fires-near-me		State/Territory Government	
	EmergencyWA	https://www.emergency.wa.gov.au/		State/Territory Government	
	TASALERT	http://alert.tas.gov.au/Pages/Home.aspx		State/Territory Government	
	Rural Fire Service (QLD)	https://www.ruralfire.qld.gov.au/map/Pages/default.aspx		State/Territory Government	
	Fire Incident Map (WA)	https://pfes.nt.gov.au/fire-and-rescue-service/fire-incident-map		State/Territory Government	
	ACT Emergency Services Agency	https://esa.act.gov.au/		State/Territory Government	
	Australian Flood Risk Information Portal	https://afrip.ga.gov.au/flood-study-web/#/search		Geoscience Australia	
	Australia Rainfall and River Conditions	http://www.bom.gov.au/australia/flood/index.shtml		BOM	

Topic	Name	URL	Datasets available	Maintainer	Notes
	Australian Exposure Information	https://portal.aeip.ga.gov.au/		BUSHFIRE & NATURAL HAZARDS CRC	GA
	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/		NSW State Emergency Services	
Pastures	Pastures from Space	http://dafwa.maps.arcgis.com/apps/webappviewer/index.html?id=53c41a43783540dabca26ceb69a2ea0f	NO	DPIRD WA	layers don't appear to show in portal
	Monthly NDVI averages for Australia	http://www.bom.gov.au/jsp/awap/ndvi/index.jsp	YES	BOM	National or state maps
	Australian Landscape Water Balance	http://www.bom.gov.au/water/landscape/		BOM	
	Travelling Stock Reserves - State Classification Map	https://trade.maps.arcgis.com/apps/webappviewer/index.html?id=dd585551cd5c4320bfcd2d671d8f2364	NO	NSW Local Land Services	https://www.arcgis.com/home/item.html?id=dd585551cd5c4320bfcd2d671d8f2364
Weather	MetEye	http://www.bom.gov.au/australia/meteye/		BOM	
	National Drought Map	https://map.drought.gov.au/		Australian Government	
	Recent and historical rainfall maps	http://www.bom.gov.au/climate/maps/rainfall/?variable=rainfall&map=totals&period=daily&region=nat&year=2020&month=10&day=26		BOM	Rainfall totals, deciles, percentages, anomalies and droughts
	Climate outlooks - weeks, months and seasons	http://www.bom.gov.au/climate/outlooks/#/rainfall/summary		BOM	
Diseases & parasites	Bluetongue Virus Zone Map	https://namp.animalhealthaustralia.com.au/public.php?page=pub_home&program=2	Yes	Animal Health Australia	part of the National Arbovirus Monitoring Program (NAMP)
	Paralysis tick				
	National Flying-fox monitoring viewer	http://www.environment.gov.au/webgis-framework/apps/ffc-wide/ffc-wide.jsf		DAWE	

Topic	Name	URL	Datasets available	Maintainer	Notes
Elevation	ELVIS - Elevation and Depth - Foundation Spatial Data	https://elevation.fsdf.org.au/	YES	ICSM	
Soils	Visualising Australasia's Soils	https://data.soilcrc.com.au/map	YES	CeRDI	
	eSPADE	https://www.environment.nsw.gov.au/eSpade2WebApp	YES	NSW Planning, Industry & Environment	https://creativecommons.org/licenses/by/4.0/
Water	Visualising Victoria's Groundwater	https://www.vvg.org.au	YES	CeRDI	
	Australian Groundwater Explorer	http://www.bom.gov.au/water/groundwater/explorer/map.shtml	YES	BOM	
Various	SEED (Sharing and Enabling Environmental Data in NSW)	https://geo.seed.nsw.gov.au/Public_Viewer/index.html?viewer=Public_Viewer&locale=en-AU	YES	NSW Government	
	ABS Maps	https://itt.abs.gov.au/itt/r.jsp?ABSMaps	YES	ABS	
	ABARES Map	https://data.agriculture.gov.au/geonetwork/srv/eng/catalog.search#/map	YES	Australian Government	
	Natural Resource Information	https://maps.agric.wa.gov.au/nrm-info/	YES	WA Government	
	National Map	https://nationalmap.gov.au/	Yes	Australian Government	
	Victoria Unearthed	https://mapshare.vic.gov.au/victoriaunearthed/	YES	EPA VIC	
	LASSI - Land and Survey Spatial Information	https://maps.land.vic.gov.au/lassi/		VIC DELWP	
	Landscape Data Visualiser	https://maps.tern.org.au/#/	YES	NCRIS, TERN, ANU	
	NatureKit 2.0	https://naturekit.biodiversity.vic.gov.au/	SOME	VIC DELWP	

Table 5.10 - Useful related data collections

Name	type	URL
Australian Abattoir locations (2014)	Google map	https://australianabattoirs.com/2014/11/07/australian-abattoir-locations/
MLA:		
Cattle numbers - as at June 2019 by NRM region	PDF map image	https://www.mla.com.au/globalassets/mla-corporate/prices--markets/documents/trends--analysis/fast-facts--maps/2020/mla-cattle-numbers-map-2020-at-june-2019.pdf
Cattle herd - Population changes : 2018-19 on 2017-18 percentage change	PDF map image	https://www.mla.com.au/globalassets/mla-corporate/prices--markets/documents/trends--analysis/fast-facts--maps/2020/mla-cattle-herd-population-changes-map-2018-19.pdf
Cattle projections	PDF (quarterly reports)	https://www.mla.com.au/prices-markets/Trends-analysis/cattle-projections/
ABARES Insights: Snapshot of Australian Agriculture 2020	PDF report	https://daff.ent.sirsidynix.net.au/client/en_AU/search/asset/1029981/0
ABS - Boundaries: LGAs, POAs, ADDs, NRMRs, SEDs etc	datasets	https://www.abs.gov.au/websitedbs/d3310114.nsf/home/digital+boundaries
ABARES data catalogue	datasets	https://data.agriculture.gov.au/geonetwork/srv/eng/catalog.search#/home
NCI	datasets	http://dapds00.nci.org.au/thredds/catalogs/fk4/catalog.html
Environment.gov.au Open Data	datasets	https://www.environment.gov.au/about-us/environmental-information-data/open-data

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