

Productivity and Biomass of Australia's Rangelands: Towards a National Database

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Abstract

This paper reviews information about field observations of vegetation productivity in Australia's rangeland systems and identifies the need to establish a national initiative to collect net primary productivity (NPP) and biomass data for rangeland pastures. Productivity data are needed for vegetation and carbon model parameterisation, calibration and validation. Several methods can be used to estimate pasture productivity at various spatial and temporal scales, ranging from *in situ* measurements to satellite-based approaches and biogeochemical modelling. However, there is a barrier to implementing national vegetation and carbon modelling schemes because of the lack of digitised and readily available data derived from field observations, not because of the lack of modelling expertise. Our main goal in this paper is to explore the potential for consolidation of existing NPP and biomass databases for Australian rangelands. A protocol structure was proposed to establish a productivity database for Australia. The TERN (Terrestrial Ecosystems Research Network) national field data network for rangeland pasture productivity monitoring and modelling team could potentially coordinate the database. Government agencies and national and international research institutions could use the outputs from productivity models to inform greenhouse gas emissions and in measuring mitigation activities relevant for reporting against the United Nations' Sustainable Development Goals and other international obligations. Other applications include monitoring fire danger, tracking ecological restoration and protection, and estimating fodder availability. Australian researchers have the tools needed to succeed in creating such a national database and a robust community of practice to curate it, enhance it and benefit from its availability.

Keywords: arid/semi-arid rangelands, biophysical models, land management, productivity database, rangeland monitoring and management, vegetation and carbon modelling

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Introduction

Most of the Australian continent ($\approx 75\%$) is covered by rangeland systems composed of savannas, woodlands, shrublands and native and non-native grasslands (Bastin et al., 2009). Here, we adopt the broad rangeland system definition that includes any of the biomes mentioned. Non-forest vegetation covers over 70% of the vegetated land surface and represents about half of Earth's terrestrial productivity. However, non-forest vegetation contributes less than 20% of global biomass (Pan et al., 2011). Compared to forest systems that account for 80% of Earth's total plant biomass (Kindermann et al., 2008), the collection of non-forest data for model calibration and validation, such as rangelands, has received less attention. Only approximately a tenth of Australia's carbon is stored in forests, while about two-thirds is held in Australia's arid and semi-arid biomes, of which two-thirds is stored below ground (Donohue et al., 2012; Poulter et al., 2014).

The Terrestrial Ecosystems Research Network (TERN, <https://www.tern.org.au/>) Surveillance Project uses a spatially extensive network to monitor more than 600 sites distributed through the country along environmental gradients and key biomes. TERN is Australia's land ecosystem observatory, which measures and records terrestrial ecosystem attributes and condition over time, from continental scale to field sites, at hundreds of representative locations (TERN, 2020). Data collected by TERN are standardised, integrated and converted to model-ready data that enable users to track and interpret changes in land ecosystems. However, not all TERN programs collect vegetation productivity or biomass data (e.g. TERN SuperSites). Rangeland net primary production has been measured once at about 180 sites and documented in the Biomass Plot Library (<http://www.auscover.org.au/datasets/biomass-plot-library/>), a TERN AusCover initiative that created an inventory of above-ground biomass data for model calibration and validation.

A study by Roxburgh et al. (2004) concluded that "... current empirical database on growth and carbon dynamics in arid Australia is insufficient to satisfactorily calibrate or validate current continental-scale models, and that more empirical work in Australian arid ecosystems is urgently required ...". Since then, a significant amount of data has been collected, such as the resources available

in the TERN network, in addition to data that are not widely available to researchers. Despite this, the problem identified by Roxburgh et al. (2004) remains relevant today. From a modeller's perspective, consistent biomass data from rangeland systems are under-represented in most available data collections. There is no empirical database in Australia with coverage across diverse biomes to validate national-scale productivity models. The lack of a consistent database leads, amongst other things, to great variability in model estimates. In a model intercomparison study, this variability has ranged fivefold from 0.67 to 3.31 GtC per year (Roxburgh et al., 2004). More recently, Haverd et al. (2013a) found some model discrepancies in the arid biomes and larger discrepancies in temperate regions (see Figure 17 in Haverd et al., 2013a).

A well-curated productivity database would assist in modelling practices. The outputs from productivity models are used for specific policy or management initiatives in Australia, e.g. the Australian Government's Joint Agency Drought Taskforce (<https://www.pmc.gov.au/domestic-policy/joint-agency-drought-taskforce/>) for reporting GHG emissions and measuring mitigation activities that are relevant for reporting against the United Nations Sustainable Development Goals (SDG) and the National Determined Commitments of the Paris Agreement (Griggs et al., 2014; United Nations, 2015). The assessment of sustainable livestock densities and tracking changes in the long-term productivity of rangelands helps to measure progress against SDG No. 12: "responsible consumption and production". Field observations of vegetation structure and biomass have helped determine the proportions and distributions of C_3 and C_4 grasses in Australia (Hattersley, 1983). A rangeland productivity database is critical for generating robust and properly calibrated model outputs. In addition to empirical and quantitative modelling approaches, productivity model outputs can be used for technological applications in computing science, such as artificial intelligence and machine learning (Musib et al., 2017). This field of science is rapidly evolving, and site-based training data in particular are the currency. In machine learning, data are used for model calibration, validation, and to adjust internal algorithms.

One of the objectives of the work reported in

this paper was to develop a protocol structure for an Australian rangeland productivity database. We focus on the amount of relevant existing data that has not been curated for public release. There is only a limited amount of time to make this data available as the custodians of the data move to other projects or retire.

In the following sections, we describe the spectrum of users of field observations and the applications of the end-products. We review the literature and list rangeland field observations in which NPP and biomass have been directly or indirectly measured in Australia.

Data and Data Users

The range of users of the rangeland database includes researchers, land managers and government. The researchers group encompasses a broad diversity of users, from those working with vegetation productivity models to fire scientists and applied ecologists. This group uses field data to derive model parameters and validate predictions and projections at various temporal and spatial scales. Model outputs contribute to assessments, from the paddock to national and global levels. The land managers group includes primary producers and those who provide advice to producers (e.g. agri-businesses, extension officers, NRM groups). Land managers can make use of the field observations by incorporating them into management decisions and practices, especially when the information is provided to them in processed form, often as part of broader information packages. Local state, territory and national governments use field observations to build their assessment and accounting systems, which are used to provide information to land managers, develop education and extension materials, support policies and meet national and international reporting obligations. On the latter, such reporting systems are heavily calibrated with observations. These are used to report annual carbon emissions and sinks from the land sector to the United Nations Framework Convention on Climate Change (UNFCCC), and towards the 2030 SDG.

Governments and institutions use the outputs and recommendations from land managers and researchers in broader decision-making processes. Government agencies need to report, for example, carbon emissions at the national scale, fire danger

and environmental conditions (e.g. State of the Environment). The outputs of productivity models help to estimate fodder availability at regional scales and yield projections for drought declaration, monitoring and relief (Nelson et al., 2010). These outputs help government agencies and institutions to engage with the public, inform policy recommendations, and report against international treaties and other obligations such as the Global Primary Production Data Initiative (GPPDI), the NPP Multi-Biome datasets (Olson et al., 2001), UNFCCC and SDG.

The interest in modelling productivity of rangeland systems has two main drivers: economic and environmental. The contribution of the agricultural industry (crops and livestock) to the Australian economy was about AU\$60 billion in 2018 (ABARES, 2018), which ranked above the 10-year average despite the drought conditions, and it contributes about 3% to the Australian gross domestic product. The contribution to the Australian economy from rangelands is estimated at about AU\$5 billion per year (Foran et al., 2019). The main overseas markets for agricultural products that depend on production in rangeland systems are China, Japan, the USA, the European Union, Indonesia and the Republic of Korea (ABARES, 2018). Monitoring of rangelands is also required for carbon accounting (Metcalf, 2014), to understand species distributions (Harris et al., 2013) and soil health, e.g. via the Australian DustWatch Program (Leys et al., 2020).

Different types of modelling have varying data intensity requirements. For example, the C-Store system (Donohue & Renzullo, 2015) is an Australian remote-sensing and observation-driven carbon assessment modelling platform that assesses rangeland productivity at the national scale at a relatively fine spatial resolution. The C-Store system is data driven, especially using remotely sensed data, and accounts for temporal dynamics of vegetation. C-Store can also produce estimates of model uncertainty. Maximum model simplicity and computational efficiency were essential criteria in the development of the C-Store system. The vegetation monitoring capacity of C-Store is calibrated to field observations. Higher numbers of observations across Australia have a positive impact on model accuracy and in reducing uncertainty.

The Pastures from Space (www.pasturesfrom-space.csiro.au) model (Mata et al., 2004) assumes that land managers would benefit from better information on which to base production decisions. It also assumes that sustainable production may not be achieved because of the lack of information to make sound management decisions on feed resources. Pastures from Space uses remotely sensed data to provide estimates of pasture production during the growing season (Hill et al., 2004; Edirisinghe et al., 2011; Smith et al., 2011). In recent years, farmers have accounted for about 70% of total users logging into the Commonwealth Scientific and Industrial Research Organisation (CSIRO)'s systems seeking estimates of pasture biomass and growth rates. One limitation of Pastures from Space is that it has little overlap with rangeland systems. Pastures from Space covers a portion of rangeland in New South Wales (NSW), but none in South Australia, Western Australia, the Northern Territory or Queensland. The main outputs of the model are pasture biomass, or feed on offer, and pasture growth rate estimates. Field observations are used to calibrate the model and validate its outputs. The Pastures from Space model has not been updated since November 2018, and as a result, producers are unable to access up-to-date data. The Pastures from Space program could be improved and updated by accessing the type of database proposed in this article.

A Dynamic Global Vegetation Model (DGVM) and land surface models can simulate shifts in potential vegetation, and its associated biogeochemical and hydrological cycles, as a response to changes in climate. DGVMs generally combine biogeochemistry, biogeography, and disturbance sub-models (e.g. wildfire) and are able to simulate carbon, water and energy exchanges between the land surface and the atmosphere. DGVMs generate outputs at sub-diurnal to century time scales (Arora, 2002; Pitman, 2003). The state and trend of carbon, water and nutrient pools are determined by modelling the flows of energy and materials between them in response to weather and a variety of natural and human disturbances (Cramer et al., 2001). Vegetation is typically classified into plant functional types, which differ in their physiological and phenological attributes (Reick et al., 2013). Depending on their sophistication, DGVMs

represent a variety of natural (e.g. fire) and human disturbances (e.g. land-use change), and associated vegetation dynamics (Sitch et al., 2003; Haverd et al., 2018). In hindcast mode, i.e. modelling historical biomass, DGVMs such as the CABLE model (Haverd et al., 2018) use carbon pool data and vegetation field observations for model evaluation. They are also an essential component of the multiple constraints approach. This approach uses a suite of observations to minimise uncertainty in model performance through formal parameter estimation (Raupach et al., 2005). Biomass data are not the most constraining in this context because of spatial and methodological variations, and the inclusion of multiple observation types mitigates bias from any single type. The pattern of biases varies regionally and through time and can help identify structural issues that relate to un-modelled or poorly modelled processes (Haverd et al., 2013a).

For Australia, field observations of biomass, leaf NPP (as litterfall) and soil carbon (Raison et al., 2003; Barrett, 2013) were combined into a DGVM with stream flow and Eddy covariance flux measurements to produce estimates of continental productivity (Monteith & Unsworth, 2013). The outputs showed significantly smaller uncertainties at regional scales than previous estimates (Haverd et al., 2013a). These results were incorporated in the first comprehensive Australian carbon budget (Haverd et al., 2013b). The model is driven by remotely sensed vegetation, and biomass field observations were used to validate hindcast results and reduce model uncertainty.

Fire scientists and ecologists are also interested in rangeland and pasture data. For example, fire danger in rangelands is driven by intermittent periods of biomass availability following significant precipitation events or long-term climate oscillations (Greenville et al., 2009). Understanding standing biomass, and the rangeland's responsiveness to precipitation, is important to assess accurately fire risk and fire-related carbon emissions. In applied ecology, for example, Gould et al. (2015) used field observations to validate a vegetation index derived from remotely sensed data, subsequently used to identify potential wildlife refuges. Once the vegetation index was validated with the field observations, it was possible to develop a method for finding areas likely to function as refuges against

drought and climate change. Gould et al. (2015)'s method assumes that locations where vegetation productivity is high and stable during drought may act as refuges. Such locations are likely to provide a more reliable supply of habitat resources for a wide range of species. Gould et al. (2015) found a stronger relationship between satellite data and field observations of vegetation biomass and productivity in white gum (*Eucalyptus* sp.) woodland than kangaroo grass (*Themeda triandra*) communities. The method referred to above has been tested in the Australian Tasmanian Midlands. In another ecological example, researchers used field observations and satellite data to monitor the negative impact of feral horses (Driscoll et al., 2019) on native grasslands in the Australian Alps (Porfirio et al., 2017).

Several applications have been developed to improve farming practices, which connect information at the farm level to a broader system managed by agronomists or researchers. For example, the AgWorld platform (<https://www.agworld.com/au/>) allows users to collect data at every level of their operation and enables them to freely share the data. The BackPaddock® application (Back Paddock Company, 2020) is similar to AgWorld, except that producers can keep track of soil test results. The Drought Feed Calculator app, developed by the New South Wales Department of Primary Industries, can be used by producers to calculate the best feed ration. The start-up Digital Agriculture Services (<https://digitalagriculture.com.au/>) provides rural data and analytics services to better predict and manage agriculture investment and commerce. There is a growing number of Enterprise Resource Planning packages used by producers that provide supply chain monitoring and certification against industry-led metrics.

Existing Rangeland Productivity Observations in Australia

In this section, we describe several existing databases that contain field observations of rangeland productivity in Australia (Table 1). The description includes the name of each dataset, together with basic information about a selection of datasets that are publicly available. We acknowledge that this list is not complete, but it provides an overview of the different groups in Australia interested in collecting this type of information, and the context in which

the data are used. There are several methods that can be used to measure ground cover, biomass and composition, and remote sensing is a rapidly expanding area. This includes both satellite information and local equipment such as ground-based LIDAR that generate large volumes of point cloud data. When these new datasets merge with traditional physical measures, they can generate a rich volume of data with different granularities. However, how these datasets merge together is critical, and if they sit in silos and therefore are not properly connected, they cannot be fully utilised.

The Global Primary Production Data Initiative and the NPP Multi-Biome Dataset

The Global Primary Production Data Initiative (GPPDI) and the NPP Multi-Biome datasets (Olson et al., 2001) were established by the International Geosphere-Biosphere Programme (IGBP, <http://www.igbp.net/>) and compiled NPP observations across the world to improve the supply, management and use of the data and information needed to attain IGBP's scientific goals. The database covers 2500 sites and underwent an extensive review under the Ecosystem Model-Data Intercomparison (EMDI) process (Olson et al., 2011, 2013). This long-term program was used to improve worldwide modelled estimates of terrestrial NPP for different biomes (Prince et al., 2001; Zheng et al., 2003, 2004) and in the global EMDI project (Olson et al., 2011, 2013). The GPPDI dataset spans the period between 1931 and 1996, which unfortunately is not covered by most current satellite data widely used in NPP and biomass models at national and global scales. These field observations, however, can be used with data from the Landsat Satellite Missions (US Geological Survey, 2018) that cover a period from 1972 to date, or to validate and calibrate hind-cast model runs. Although these datasets have very few points in Australia, the methods and protocols used to collect and combine the data could be used in the future to expand the dataset.

The GPPDI dataset is divided into three categories, namely: Class A representing intensively studied or well-documented study sites; Class B representing more extensive sites with less documentation and site-specific information available; and Class C representing regional collections of half-degree latitude-longitude grid cells. Class C

is less well documented compared with Class A and B, and it may be regarded as less reliable. The Australian continent is represented in the GPPDI dataset with fourteen Class A and seven Class B sites, comprised of C_3 and C_4 grasses, forests and shrublands.

The Nutrient Network Dataset

The Nutrient Network (NutNet, <https://nutnet.org/>) is hosted by the University of Minnesota and started collecting data in 2007. The NutNet project aims at quantifying human impacts on grassland systems at the global scale. The dataset covers more than 40 sites around the world. The specific goals of NutNet are to:

- collect data from a broad range of sites in a consistent manner to allow direct comparisons of environment-productivity-diversity relationships among systems around the world; and
- implement a cross-site experiment requiring only a nominal investment of time and resources by each investigator, but quantifying community and ecosystem responses in a wide range of herbaceous-dominated ecosystems (from desert grasslands to Arctic tundra).

Grassland ecologists around the world may become members of NutNet, but they are required to carefully follow research protocols for sampling. Australian grasslands are represented in the NutNet dataset by 13 sites (Morgan et al., 2016). The NutNet database has been used, for example, to investigate the relationship between plant productivity and species richness (e.g. Adler et al., 2011) and to study ecological interactions in grasslands (e.g. Seabloom et al., 2013; Ziter & MacDougall, 2013; Lind et al., 2017; Anderson et al., 2018).

NPP Multi-Biome: VAST Calibration Data

The NPP Multi-Biome: VAST Calibration Data provides observations from Australia for use in parameterising the Vegetation and Soil-carbon Transfer (VAST) Model (Barrett, 2002, 2013). The VAST dataset contains 588 individual sites across Australia, with estimates of above-ground NPP based on cut grass swards and visual assessment of growth, litterfall (leaf and fine twig),

measurements of above-ground biomass (phytomass), fine litter mass, and measurements of soil carbon concentration and soil bulk density in surface layers (0–150 mm depth interval). These data were derived from 174 original literature references describing study sites throughout Australia. The data cover the period between 1965 and 1998, and sites used in VAST were in steady state, i.e. ecologically, in climax systems. The VAST model and dataset were used to estimate and calibrate carbon dynamics in native and human-modified environments in Australia (Porfiriio et al., 2010).

Western Australian Rangeland Monitoring System

The Western Australian Rangeland Monitoring System (WARMS) is a set of about 1620 permanent sites in the pastoral rangelands of Western Australia, although it includes some sites on land that has been removed from grazing and added to the conservation estate (Watson et al., 2007). The system is designed to assess changes in the perennial component of the vegetation. In shrubland vegetation, a direct census technique is applied, while in grassland areas the frequency and species composition of the perennial understorey is measured. While perennial biomass is not directly measured in either grassland or shrubland sites, it could be estimated for some purposes. The benefit of using a dataset such as WARMS is that it has a clear site stratification protocol and sites across all the grazed rangelands of Western Australia ($\approx 892,000 \text{ km}^2$), and it is supported institutionally in the long term. Grassland sites are assessed every three years, with shrubland sites every five years. The system was installed over a number of years, with the full set of planned sites installed by 1999, noting that a small number of site modifications are necessary in each year due to infrastructure or other changes (Watson et al., 2007).

A feature of rangeland ecosystems is that they follow state-and-transition model dynamics, rather than a linear Clementsian (climax) succession model (Clements, 1936). Thus, it is important to consider large changes in the capacity of a site to produce biomass due to state change. Understanding the frequency and likelihood of such changes is necessary to model this. Watson and Novelty (2012) used the WARMS dataset to

identify transitions observed on 306 grassland sites and 919 shrubland sites between 1993 and 2010, and suggested that state change had occurred on 11% of grassland sites and 1% of shrubland sites.

Aussie GRASS: Australian Grassland and Rangeland Assessment by Spatial Simulation

The Aussie GRASS project was established in 1996 as a multi-agency collaborative project and involved eight Australian agencies^a (Carter et al., 2000a,b; Dyer et al., 2001; Richards et al., 2001; Tupper et al., 2001). It was funded by Land & Water Australia, led by the Queensland Department of Natural Resources and Mines, and involved the CSIRO and all rangeland states and territories in Australia. Aussie GRASS is an open-access national rangeland model that monitors pasture growth and biomass during drought and other climatic conditions (Littleboy & McKeon, 1997; McKeon et al., 2004). Aussie GRASS is based on comprehensive datasets (Day et al., 1997; McKeon, 2010) and currently provides 2000 reports per month to landholders, researchers and government (Owens et al., 2019). The model GRASP was derived from measures of NPP, quality and composition using the SWIFTSYND methodology (Day & Philp, 1997) from several datasets including 89 sites in 47 localities, giving 179 site-by-year combinations with three to seven observations over the growing season at each site (Day et al., 1997). Many other SWIFTSYND and grazing trial datasets in theses and industry/government-funded projects have been used to calibrate GRASP, including several SWIFTSYND sites that have been continuously monitored since 1986 (Cobiac, 2006; McKeon, 2010; Whish, 2017; Cowley et al., 2019). The dataset used to calibrate GRASP parameters within the Aussie GRASS framework at every grid cell location across the northern and southern rangelands of Australia was based on satellite imagery and 'spider mapping' with over 220,000 visual estimates of pasture biomass across Queensland, and was verified with 1300 measurements of pasture biomass between January 1994 and August 1995 (Hassett et al., 2000). This initial Queensland dataset was

augmented with a further 59,500 visual estimates of pasture biomass (and verified with pasture measurements) across the southern rangelands in New South Wales, South Australia and Western Australia (Richards et al., 2001), and 110,000 visual estimates across the northern rangelands of the Northern Territory and the Kimberley region of Western Australia (Hall et al., 2001).

The Aussie GRASS model is used to explore herbivore carrying capacity, land sustainability, drought alerts and land degradation, and has been used extensively by government in relation to drought. The Aussie GRASS model was developed in collaboration with stakeholders and clients over several workshops, with the objective of transferring technology and sharing validation methods (Stone et al., 2019). This national program delivers information to land care groups, land managers and executive government about key biophysical processes associated with pasture growth (degradation and recovery) at paddock, regional and national scales. National Oceanic and Atmospheric Administration satellite imagery (NOAA, US Department of Commerce, <https://www.noaa.gov/satellites/>) was used to complement the system, providing regular estimations of grassland and rangeland biomass and productivity. The estimations were modelled on a daily time-step but presented publicly on a monthly time-step. The project was also scoped to generate a grassland and rangeland productivity seasonal forecasting system in collaboration with the Australian Bureau of Meteorology (<http://www.bom.gov.au/>) and potentially a long-term forecast based on general circulation models in collaboration with the US Scripps Institution of Oceanography (<https://scripps.ucsd.edu/>) and the CSIRO.

The Aussie GRASS project also had a social component that was used to collect information and make users aware of the products and how to use them. Project staff, primary producers, agribusiness and government personnel participated in 25 workshops, each tailored based on the needs of the different regions, to create awareness of the project and obtain feedback on prototype products. Up-to-date products were made available on information systems operated

^a The late Dr Barry White, National R&D Coordinator for Land & Water Australia, fostered collaboration across Australia on rangeland data and modelling as part of the Climate Variability in Agriculture Program (CVAP, <http://lwa.gov.au/programs/climate-variability-agriculture-program>).

by the Queensland Government via the Queensland Centre for Climate Applications, such as The Long Paddock (<https://www.longpaddock.qld.gov.au/>) and Aussie GRASS (<https://www.longpaddock.qld.gov.au/aussiegrass/>) websites. Issues arose from the participative workshops related to the accuracy of the products and the applicability of seasonal climate forecasting in some regions (Carter et al., 2000a,b; Dyer et al., 2001; Richards et al., 2001; Tupper et al., 2001). Most participants preferred to have access to a State map (at a coarser pixel resolution) and a site-specific map (at a finer pixel resolution). ERDAS LAN files were made available on the website, and they were customised to satisfy the needs of individual clients. Other feedback related to cartographic adjustments, which were required to improve map readability.

Australian Fuel Biomass

Samples of litter and grass fuels were collected from 133 sites across Australia for studying continental patterns of landscape fire activity, severity and fuel consumption (Prior et al., 2017), which included rangeland and forest sites. Samples from the 133 sites were oven-dried and weighed to estimate moisture content and to convert field-fresh weights of fuel biomass to dry matter weight. The data are publicly available via an online repository (Prior et al., 2017). Murphy et al. (2019) used these data to estimate biomass consumption during fires in Australia and concluded that fire management on fire-prone tropical Australian savannas could be implemented to reduce carbon loss and emissions, but that care should be taken to avoid establishing a grass-fire cycle (Bowman et al., 2007) which could significantly increase emissions. Other examples of (unconsolidated) data collected for fire modelling studies, and independent from Prior et al. (2017)'s work, are:

- A dataset collected for a program of the Bushfire Cooperative Research Centre.
- The Victorian Forest Monitoring Program.
- A dataset collected in old-growth *Eucalyptus regnans* forest (datasets 1–3 are described in Volkova et al., 2018).
- Fuel consultations across the northern savanna (Bowman et al., 2007).
- Grass biomass data from 160 plots in northern Australia (Bowman & Prior, 2004).

- A consultation of C_3 and C_4 grasses across different Australian biomes (Murphy & Bowman, 2009).

None of the above datasets has been consolidated.

The Australian Carbon Database v1.0

The Australian carbon database v1.0 (Lawson & Donohue, 2015) is based on a literature search that found a total of 621 observations from 157 sites across Australian rangeland systems. This database describes 15 specific carbon pools, such as above-ground tree biomass, grass leaf biomass and soil carbon biomass, with only 16 observations being accompanied by error estimates, and with only 15 sites having repeated measures of any kind. The median footprint of the observations is about 0.5 ha. Key features of this database are:

- Includes biomass (plant material, either live or dead) and soil carbon stores (both above-ground and below-ground carbon).
- Compiles error estimates and other metadata related to data reliability.
- Discriminates between specific types or pools of carbon (e.g. leaves, stems, roots, litter) and between trees and grasses.
- Values are reported on a per-ground-area basis, as opposed to an individual plant basis.

The database is publicly available, but it has not been uploaded to a public repository.

Pastures and Climate Extreme Experiment

Funded by Meat and Livestock Australia Ltd (MLA, <https://www.mla.com.au/>) with co-investment from Western Sydney University, the Pastures and Climate Extremes (PACE) project was designed to provide novel insights into the potential impacts of future, more extreme, climatic conditions on pasture systems across Australia. The experiment ran between 2017 and 2020 and used technology inside a glasshouse to simulate different climatic conditions. The setup included 12 pasture species and mixed species sward types, with 10 different species commonly used in pasture-based meat and dairy farming including a range of C_3 and C_4 grasses. Legumes and native grasses (*Rytidosperma caespitosum*, *Themeda triandra*) were also included in the study. The experimental climate conditions examined in

this work focused on a winter/spring drought scenario involving a 60% reduction in precipitation based on a 128-year record of 650–750 mm annual precipitation events. The drought treatment operated in addition to a delayed autumn break that shifted the pattern of water availability at the end of the warm growing season (Pook et al., 2006; Kiem & Verdon-Kidd, 2010). Additionally, a subset of pasture swards was exposed to a +3°C warming treatment using infrared ceramic heaters in a factorial cross with the drought conditions. Pasture plots were 2.5 m × 2.5 m, with a core sampling area of 1 m² to determine annual and seasonal productivity above and below ground. Biomass harvests were sorted to account for proportional contributions of any weeds, and regular assessments of plant tissue chemistry were conducted for all species. Each plot was additionally monitored with a camera to track shifts in pasture canopy colour and cover, using daily imaging to examine short-term responses to changing environmental conditions. The outcomes of this project were used to inform strategies for maintaining sustainable pastures in Australia under climate change scenarios. The PACE facility is located at the Western Sydney University's Hawkesbury Campus at Richmond (NSW, Australia), and initial data products were made available to the public in 2019 (A. C. Churchill, formerly at the Western Sydney University, now University of Minnesota, pers. comm., 2020).

NPP Grassland: Charleville

The NPP Grasslands Charleville dataset comprises measurements of above- and below-ground biomass, productivity and litterfall data for a native C₃ and C₄ grassland near Charleville (26°24'07"S, 146°14'43"E, elevation 301 m above sea level) in southern Queensland. The NPP studies were conducted over a 12-month period from 1973 to 1974 using harvest techniques, and the data were used to calibrate a primary productivity model for livestock carrying capacity. Annual net primary production was estimated as the sum of above-ground peak standing crop (live + dead) and root increment. This dataset has been uploaded to a public repository (Table 1).

Miles and Condamine, Southern Queensland: Vegetation Assessment

An assessment of native grassland systems was undertaken at two sites (Sites 1 and 2) in the Miles

and Condamine region of southern Queensland (Abbott et al., 2017). Field work was undertaken to sample natural vegetation based on the method developed by Tohill et al. (1992). Further walk-through samples were conducted for each of the sites to determine overall biodiversity. Biomass estimates were calibrated using 10 cut, dried and weighed quadrats for each site. Cover estimates were calibrated using 10 photographs of quadrats per site, which were classified into cover and bare earth using remote sensing (Abbott et al., 2017). Site 1 was dominated by native perennial grasses (*Aristida* sp.) and exotic perennial grasses (*Cenchrus ciliaris* or buffel grass), with approximately 10% native perennial grasses. Site 2 was dominated by the native perennial grasses *Eriachne mucronata* (≈43%) and *Chloris divaricata* (≈8%), along with a significant component of exotic perennial grasses: *Bothriochloa pertusa* (≈11%), *Megathyrsus maximus* (≈11%) and *Urochloa mosambicensis* (≈9%). Readers are referred to Abbott et al. (2017) for a full description of this work and access to the electronic database.

Unpublished or Unavailable Datasets

We know of a large amount of field observations collected in rangeland systems that have not been made publicly available, often because they pre-date the internet age. The amounts of digital and non-digital data that are stored in public and private computer servers or filing cabinets are understood to be large. Current capabilities and resources available to researchers are not sufficient to curate and publish those datasets, but this may be possible with adequate investment. For example, T'Mannetje & Jones (2010) summarise 73 grazing trials from northern Australia that collected biomass information and that were routinely sampled several times per year over multiple years. During a four-year period, Graetz (1980) collected samples of sites grazed by cattle or sheep in New South Wales. Holm et al. (2003) recorded shrub biomass and herbs, forbs, ephemerals and biennials, amongst others, over 11 years, four times per year, in 10 paddocks and four exclosures from 137 sites. These comprehensive datasets are not publicly available. Datasets may be tidied and error-checked, but before becoming operational, they need metadata and instructions on the codes used and the methods by which the data were collected.

Table 1. A compilation of publicly available rangeland productivity observations in Australia. Units are expressed as they appear in the original data source.

Name of NPP-biomass dataset	Spatial coverage	Spatial resolution	Temporal coverage	Temporal resolution	Link to data or reference	Applications	Limitations
GPPDI	Global	Measurements based on sampling of small field plots (from m ² to 1 ha). Gridded data are half-degree latitude-longitude grid cells.	The point and gridded measurements included here cover the period from 1931 to 1996. This coverage does not include all years for all sites.	Annual NPP estimate in g C/m ² /year (carbon content of dry matter weight).	https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1033	<ul style="list-style-type: none"> Modelling Natural resource inventory and management Carbon accounting 	<ul style="list-style-type: none"> Temporal resolution for current modelling applications
NPP Multi-Biome	Global	The boreal forest study plots were between 0.09 and 0.25 ha in size. The tropical forest study plots were between 0.0025 and 4.4 ha in size. The C ₃ and C ₄ grassland study plots were between 0.0025 and 0.7 ha, and between 0.06 and 0.25 ha in size, respectively.	1939–1996	Generally, one month for grasslands and up to one year for forests.	https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=653	<ul style="list-style-type: none"> Modelling Natural resource inventory and management Carbon accounting 	<ul style="list-style-type: none"> Temporal resolution for current modelling applications
Nutrient Network: A Global Research Cooperative	Global	The core experiment will be a completely randomised block (environmental gradient) design with three blocks, 10 treatments per block, and three replicates per treatment ($n = 30$ total experimental units). Each experimental unit will be 5 × 5 m in size, with the experimental units separated by at minimum 1 m walkways. The corners of the plots should be marked permanently.	2007 – ongoing	Data collected during growing season. Biomass g/m ² and cover (fraction).	https://nutnet.org/	<ul style="list-style-type: none"> Modelling Natural resource inventory and management Carbon accounting Rehabilitation of degraded landscapes Land-use assessment/ Land-use changes 	<ul style="list-style-type: none"> Accessibility
NPP Multi-Biome: VAST Calibration Data	Australia	The observations were obtained by different authors from studies at 588 locations.	1965–1998	Annual NPP estimate in Mg C/ha/year. Above-ground phytomass in Mg C/ha. Above-ground fine debris litter mass in Mg C/ha.	https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=576	<ul style="list-style-type: none"> Modelling Natural resource inventory and management Carbon accounting 	<ul style="list-style-type: none"> Temporal resolution for current modelling applications

Name of NPP-biomass dataset	Spatial coverage	Spatial resolution	Temporal coverage	Temporal resolution	Link to data or reference	Applications	Limitations
AEKOS <i>Poaceae</i> Extraction, 2014	Australia	The data include vegetation records for the Poaceae family from the following dataset: ABARES Ground Cover Reference Sites Database, Biological Survey of South Australia – Vegetation Survey, Biological Database of South Australia, Corveg (Queensland), TERN AusPlots Rangeland Survey Program, Biological Survey of the Ravensthorpe Range (Western Australia).	1975–2013	Abundance, biomass and cover.	https://portal.tern.org.au/aekos-poaceae-extraction-2014/17370	<ul style="list-style-type: none"> Modelling Natural resource inventory and management Carbon accounting Rehabilitation of degraded landscapes Surface cover Land-use assessment/land-use changes 	<ul style="list-style-type: none"> Temporal resolution for current modelling applications Scale
Fuel biomass	Australia	Site estimations based on three transects of about 100 metres.	2001–2012	Measurements of above-ground grass and herb standing biomass and other structural characteristics. Biomass in Mg/ha.	https://figshare.com/articles/A_continental-scale_assessment_of_fuel_loads_and_consumption_by_wildfire/6203993	<ul style="list-style-type: none"> Modelling Natural resource inventory and management Carbon accounting 	<ul style="list-style-type: none"> Temporal resolution for current modelling applications Scale
The Australian Carbon Database v1.0	Australia	Dataset based on a literature search. A total of 621 observations from 157 sites were collated, describing 15 specific carbon pools (such as above-ground tree mass, grass leaf mass, soil carbon mass). Only 16 observations have accompanying error estimates, and only 15 sites have repeat measures of any kind. Median footprint of observations 0.5 ha.	1951–2012	Measurements of above-ground standing biomass and other structural characteristics. Biomass in kg/m ² .	Lawson et al. (2015)	<ul style="list-style-type: none"> Modelling Natural resource inventory and management 	<ul style="list-style-type: none"> Scale Temporal resolution for current modelling applications Accessibility
Pastures in Climate Extremes (PACE)	South East Australia, Plot experiment	Plots of 2.5 m ²	2017 – ongoing	Measurements of above-ground biomass (kg/ha) (refer to webpage for more information).	https://www.westernsydney.edu.au/hie/projects/pace_pasture_climate_extremes	<ul style="list-style-type: none"> Modelling 	<ul style="list-style-type: none"> Scale Temporal resolution for current modelling applications

Name of NPP-biomass dataset	Spatial coverage	Spatial resolution	Temporal coverage	Temporal resolution	Link to data or reference	Applications	Limitations
NPP Grassland: Charleville	Charleville site, Queensland, Australia	Each study area covered 0.7 ha. Quadrats were 1 m ² .	1973–1974	Measurements of above- and below-ground standing crop were made every 2 weeks during the growing seasons; otherwise every 4 weeks over a 12-month period. NPP in g/m ² /year; Biomass g/m ² .	https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=468	<ul style="list-style-type: none"> Natural resource inventory and management Surface cover 	<ul style="list-style-type: none"> Scale Temporal resolution for current modelling applications Accessibility
Miles and Condamine, southern Queensland: vegetation assessment	Southern Queensland, Australia	Each site consisted of five 1 m ² quadrants, randomly distributed.	November 2016	Each site measured species composition, biomass kg/ha, total cover, litter cover and grass basal area.	Abbott et al. (2017)	<ul style="list-style-type: none"> Natural resource inventory and management Surface cover 	<ul style="list-style-type: none"> Scale Temporal resolution for current modelling applications Accessibility

In an attempt to understand past and current activities, and identify contributors and interest to form an Australian productivity field-site network and community of practice, we released a consultation to find data (irrespective of public or not) to inform the need for coordination. Unfortunately, despite widespread circulation, only eight people responded to the consultation request, and while this activity partly informed our thinking, the results are not presented in any detail here, but they are available and can be requested from the lead author.

The Proposed Way Forward

Scattered and privately held data, whether in analogue or digital form, need curation and consolidation. We have provided some examples of data that are publicly available in Australia, and we would like to use this contribution to initiate a conversation on this topic and excite future work in this space. For example, the TERN Data Discovery Portal displays 170 or 186 results when using “rangeland biomass” or “pasture biomass” as key searching words, respectively. These datasets are independent from each other. The commonalities between them have to be assessed by the user before deciding to incorporate them into their modelling system. The time required to assess and validate a dataset generated by another research group is often beyond the scope and budget of most projects. There are also concerns about formatting the data so that they can be shared publicly without breaking contractual obligations. In the following sections, we discuss how the existing data may be merged into a national rangeland productivity database. We propose a protocol for the creation of a National Net Primary Productivity and Biomass Database based on the existing recommendation for data collection in Australia, taking into consideration:

- the needs of different users;
- the need for a robust community of practice; and
- the need for an operational model to make the investment attractive to potential collaborators.

Australian Rangeland Productivity Database

Globally and nationally, researchers require well-tested validation approaches that are transparent and flexible (e.g. geographic scope, spatial resolution, protocol). There is a need for good practices and protocols to guide productivity model calibration and validation. TERN has developed a protocol (Held et al., 2015) for above-ground biomass collection. This protocol and the data-sharing practices from the AusPlots Rangeland Consultation Protocols Manual (White et al.,

2012) are used to inform research, management and conservation strategies. However, existing well-regarded protocols must be considered. McKeon et al. (2009) references the GUNSYND (McKeon et al., 1990) and SWIFTSYND (Day & Philp, 1997) protocols for collection of grassland data. These were developed to feed into the GRASP model (i.e. protocols were designed by modellers) and Aussie GRASS, and were well embraced by all rangeland states (Carter et al., 2000a,b; Richards et al., 2001). These protocols have been accepted by users and used to collect significant amounts of data. At the farm level, producers also use measurements of pasture biomass to assist in their management decisions, e.g. by visual estimation in rangelands and using plate meters to estimate pasture biomass in temperate grasslands (Catchpole & Wheeler, 1992). In fodder availability estimations, pasture biomass measurements are usually combined with information on pasture quality such as protein content, digestibility and soluble carbohydrate content. There appear to be insufficient channels to share these data, and if shared, the data would have to be built with industry and producer engagement and with appropriate checks to respect privacy and commercial confidence. Researchers and modellers do not share data unless a project that plans to collect field observations is under a contractual obligation to make the data publicly available. The 'best' database will vary based on users' needs. TERN follows the FAIR (Findable, Accessible, Interoperable and Reusable) Data Principles (Wilkinson et al., 2016). These principles are useful because they:

- support knowledge discovery and innovation;
- support data and knowledge integration;
- promote sharing and reuse of data;
- are discipline independent and allow for differences in disciplines; and
- move beyond high-level guidance, containing detailed advice on activities that can make data more 'FAIR'.

One approach is to classify the existing and new data into categories following the structure proposed by the GPPDI (Olson et al., 2011), where information is classified from Class A to Class C, representing reliability of the datasets. Here, the users will determine what level of information satisfies their needs and use the data accordingly. For example, in terms

of understanding rangeland biomass and productivity for fire applications, and therefore for fire-related carbon emissions, the temporal dynamics of biomass and productivity are vital information. Fire risk in semiarid and arid rangeland and grassland is driven by biomass availability that is linked to rainfall in previous periods. So, data and models that support understanding of rangeland response to precipitation over time are crucial inputs in fire modelling systems. Therefore, data collection should span a significant temporal period to capture biomass variation over time in response to precipitation, both within and between years. This will also help validate remote sensing biomass observations that can be used in fire fuel availability analyses. In this example, long-term information is a vital characteristic to achieve a satisfactory model performance, and the same could be argued for fodder productivity models. For this type of user, long-term observations could rank higher than detailed characterisations of the species composition and structure at a specific site. A well-detailed dataset about species composition and structure may be the most important characteristic in ecological and grazing impact studies. Therefore, a database should be compiled in a way that is flexible enough to discover information and characteristics about the entries based on the different users' needs.

Data Sharing Practices

One of the biggest challenges in this proposal is to create a robust community of practice willing to follow the proposed protocols and contribute their data to a national database. The community of practice will need to recognise the intellectual property of data and the need to develop license arrangements for data usage, whether for research, education and extension or other purposes. Use of data for commercial applications will need to be considered. The intellectual property, both in the original and curated data, will need to be transparent for potential users. Setting up the data as a tangible commercial asset will provide flexibility and assist collaborative arrangements, and will help establish a framework for continuous developments into the future. License arrangements may be free or attract fees and royalties depending on the data application. We understand the community of practice as a social learning system (Wenger, 1999). Meaningful

learning requires participation of people with a common goal. The participants should have a collective understanding of ‘what matters’ and how to engage to generate more knowledge. Some of the main attributes for a functional community of practice are: imagination, engagement and alignment. We recommend a dynamic model where stakeholders, funders and end-users can benefit from being part of the community of practice and having access to the updated and curated database.

The Global Carbon Project (GCP, <https://www.globalcarbonproject.org/>) follows a similar protocol, and some of the benefits are:

- Contributors have early access to the database so they can prepare publications before it becomes publicly available.
- Stakeholders and funders can show the value of data collection through the products and services that are provided based on the data, which without the existence of the database would not be possible to achieve.
- To become part of a large group of users and beneficiaries that can provide feedback about how to improve data collection and how to improve end-products.

Here, the outcome is to offer public access to a biomass database. Based on the GCP protocol, we propose that contributors to these datasets should have access to the data beforehand. This means that information can be accessed well in advance of the data being released to the public, giving researchers the opportunity to prepare and lead publications. In this scenario, the database is curated by the contributors before being publicly released. We also propose to launch the database with a paper, with all major data contributors as co-authors, for a data journal. The associated database will have a Digital Object Identifier (DOI), which can be used to track the impact of the database and count citations for the contributors of the database.

Contributing organisations may apply for funding to organise workshops with other contributors, leading to the production of scientific material using the updated data, expanding networks and developing new collaborations. New publications should target highly ranked journals. Being part of the community of practice will give researchers the opportunity to collaborate in future publications,

expand their networks, promote their work and explore new research opportunities. The proposed approach should encourage an increased number of people to collaborate so that the database can attract more entries.

Formatting existing data for public sharing can prove cumbersome due to time and budget constraints. Data collected by private companies (e.g. Cibolabs in Australia, <https://www.cibolabs.com.au/>) or public institutions cannot be shared publicly in the current format due to contractual obligations or formatting issues. The time and labour capacity required to format the data can be expensive. Public institutions, including universities and research government organisations, may not provide the required support to researchers for long-term data management (Tenopir et al., 2011). Therefore, we suggest giving small companies and institutions or independent researchers the opportunity to apply for grants to format their data and make it publicly available through a rangeland database. If funding investments could be arranged, TERN may be an excellent choice as a partner organisation in leading and managing the database. Public access to the data may be best provided by developing collaborative arrangements with agencies that have specialised systems for public and collaborative access to large datasets, such as Geoscience Australia and the Bureau of Meteorology. An alternative to the above may be to consider a larger, nationally coordinated project to develop the rangeland database, which has been done in the past for other datasets. Examples are the development of the Bureau of Meteorology weather data through the CLIMARC (Computerising the Australian Climate Archives) and SILO projects with funding from Land & Water Australia; runoff and streamflow data throughout Australia via a LWRRDC (Land and Water Resources Research and Development Corporation) funded project (Clarkson et al., 2000); and soils data through a number of agencies. Some of the advantages of data management and sharing are (Tenopir et al., 2011):

- Different interpretations or approaches to existing data contribute to scientific progress.
- Well-managed, long-term preservation helps retain data integrity.
- When data are available, (re-)collection of data is minimised; thus, use of resources is optimised.

- Data availability provides safeguards against misconduct related to data fabrication and falsification.

To which we add:

- In situations where the researcher identifies the need to collect new data, we recommend following existing protocols in order that field observations can be easily incorporated into the national database and data sharing is possible.
- Publish the data in an open and discoverable repository: the data do not necessarily have to be open to the public, but the public should be able to know that the dataset exists.

Conclusions

There is a collective perception in the Australian scientific and modeller community that there is a lack of field observations of rangelands. We found several examples of datasets that, if combined, would cover a significant proportion of Australia's rangeland systems. Data exist but are scattered and need consolidation for ready access. We also contend that there is a vast amount of digital and non-digital data stored in public and private computer servers or filing cabinets. Retirement of current senior scientists from universities, government agencies and allied organisations in the near future could result in a significant amount of data collected over the years becoming unavailable if not properly archived in electronic databases.

We propose the development of an Australian Rangeland Productivity Database. If this concept is accepted, with either industry funding or as a government-funded project, then the next challenges revolve around ways to implement it, including selection of an organisation to lead such a project. The establishment of a national database will help to improve estimates of rangeland systems (productivity, structure) and modelling platforms, and to prioritise unrepresented ecoregions in future

field studies. We identify potential affiliates of this community and users of the proposed rangeland productivity field-site network.

Compiling existing datasets is a major task that the TERN (Terrestrial Ecosystems Research Network) could potentially achieve over future years. This task must consider that the user should be able to assess observations through a portal that can be easily queried to filter for desirable information. Researchers find it difficult to transfer information to the existing platforms, and the value of making data discoverable has not been quantified. TERN should consider the consolidation of a national rangeland productivity database, based on existing data, as one output. We emphasise that there is limited time to undertake this work. Such datasets should be regarded as a national asset that otherwise could be lost. The rangeland productivity community is seeking ways to streamline data collation and use. Incorporating biomass measurements in the TERN SuperSites protocol could be a plausible solution in the short term. The rangeland productivity community is seeking long-term monitoring and a sustainable funding model. TERN would need to manage the governance and the industry advisory committee.

Australian scientists have the tools needed to succeed in creating a robust community of practice. Government, public and private institutions should be able to provide the required resources to build this community and establish long-term collaboration across disciplines. This community should promote 'good' data sharing practices and identify project opportunities and channels to collaborate in such projects. Improved science flowing from development of the database would deliver benefits to the rangelands through better management of high-priority issues, such as tracking and managing land condition, ecological restoration and protection, drought, fire and climate change, and reduced sediment flows to waterways and the Great Barrier Reef.

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Waterhole in the Mitchell River catchment, Cape York, Queensland (Photo: Nathan Dyer).



North West Queensland Rangelands, Upper Burdekin, Indian Couch Invasion (Photo: Brett Abbott, 2006).