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Is operationalising natural capital risk assessment practicable?

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Abstract

Financial institutions are indirectly exposed to risks associated with the impacts and dependencies on natural capital and ecosystem services of the companies that they invest in, lend to, and insure. This is particularly true for banks lending to agriculture: a sector with both significant impacts and critical dependencies on natural capital. Bank lending is a vital source of new finance for the sector, which is essential to achieve sustainable intensification targets.

Yet current credit decision-making practice is still based on conventional financial and management indicators, lacking any systematic assessment of natural capital risks, especially those associated with dependencies. Operationalising natural capital risk assessment requires practicable indicators and data to evaluate the most material natural capital risks for a given sub-sector and geography, but it is unclear to what extent these are available. We assess the practicability of natural capital dependency risk indicators and data sources for a critical case study of Australian sheep production. We find that at least moderately practicable indicators and data sources are available to assess the 11 major dependency risks that are material for this industry. Challenges remain in determining risk thresholds for most indicators, and quantifying risk impacts on profitability.

Keywords

Natural capital; credit risk assessment; materiality; indicators; environmental data; sheep production

1. Introduction

In June 2012, at the 'Rio+20' Earth Summit in Rio de Janeiro, around 40 international financial institutions signed the Natural Capital Declaration (NCD), stating their intention to start integrating natural capital considerations into decision-making for all of their financial products and services, from loans to equity investments and insurance policies (Natural Capital Declaration, 2012). The event marked a watershed in financial sector acknowledgement of its systemic interactions with the biophysical environment, now widely understood across the business sector as 'natural capital', or the set of natural assets which yield flows of environmental goods and ecosystem services that have value for the economy and society (Mace et al., 2015; Natural Capital Coalition, 2016). The principal difference between 'natural capital' and earlier 'environmental' thinking in the business community is that the former places an equal emphasis on *dependencies* on the biophysical environment, in addition to the latter's awareness of *impacts* on the environment (TEEB, 2012). In other words, natural capital thinking emphasises the two-way interconnectedness of financial and biophysical systems.

An economy-wide analysis of the materiality of dependencies of different sectors on natural capital found that large-scale agriculture unequivocally tops the list (NCFA and UN Environment World Conservation Monitoring Centre, 2018). Agricultural production is highly dependent on a range of ecosystem services (provided by water, soils and biodiversity in particular) which are in turn highly vulnerable to disruption, for example due to climate change (IPCC, 2014). Agriculture has also been singled out as the leading source of impacts on natural capital. For example, food production has been associated with up to 30% of global greenhouse gas emissions and 70% of freshwater use, and agriculture is acknowledged as the main driver of species extinctions (Willett et al., 2019). The annual costs of the natural capital impacts of crop production and livestock production, combined, have been estimated at USD $2.3 trillion, or 50% more than their current market value (FAO, 2015). Agriculture is therefore highly exposed to risks arising from both its impacts and its dependencies on natural capital. These risks can affect producers directly, and thus are also indirectly relevant for agricultural investors, lenders and insurers, as well as other participants in agricultural value chains, regulators and society more generally.

At the same time, agriculture faces the challenge of needing to increase production by 60-100% on 2005 levels to feed a growing global population by 2050 (Alexandratos and Bruinsma, 2012; Tilman et al., 2011). Achieving these targets through sustainable intensification (Foley et al., 2011; Garnett et al., 2013; Hunter et al., 2017) will require substantial increases in investment, on top of the approx. USD 436 billion currently flowing into agricultural systems every year (Donckt and Chan, 2019). Hence the extent to which agricultural lending and investment decision-making takes natural capital considerations into account has the potential to significantly influence the future trajectory of agricultural systems, in terms of their productivity, resilience and impacts on the biophysical environment.

In 2012, the signatories to the NCD noted that, "At present many financial institutions do not sufficiently understand, account for and therefore value, the risks and opportunities related to Natural Capital in their financial products and services…" (Natural Capital Declaration, 2012, p. 2). The NCD signatories and supporters, re-branded as the Natural Capital Finance Alliance (NCFA) in 2016, have coordinated a long-term work programme to address these shortcomings. A 2015 NCD report identified a range of barriers preventing the integration of natural capital into financial sector decision-making, including the lack of suitable methodologies, tools and data to assess natural capital risk (Cojoianu *et al.*, 2015). The lack of suitable methodologies and tools is now being addressed, including through the development of a generic assessment framework for business, the Natural Capital Protocol (Natural Capital Coalition, 2016); a Protocol supplement specifically for the financial sector (Natural Capital Coalition, 2018); a guide to rapid assessment of natural capital dependency risks at portfolio level (NCFA and PwC, 2018) supplemented by an online portfolio assessment tool, ENCORE[1] (NCFA and UN Environment World Conservation Monitoring Centre, 2018); and a transaction-level guide to natural capital risk assessment (NCRA) in agricultural lending (Ascui and Cojoianu, 2019a). These methodologies and tools are of increasing specificity, in terms of the target users (from business, to the financial sector, to banks specifically), the level of assessment (from the whole organisation, to investment portfolios, to individual transactions) and sectoral coverage (from all sectors, to agriculture in particular).

Although the NCFA guide (Ascui and Cojoianu, 2019a) provides a methodology for undertaking NCRA, numerous barriers remain to its operationalisation in lending decision-making, despite banks' stated intentions to do exactly this (Henry, 2016; NAB, 2018; Natural Capital Declaration, 2013). The heterogeneity of natural capital impacts and dependencies in agriculture means that a sub-sector- and geography-specific approach is required (Ascui and Cojoianu, 2019a). This applies to several key elements in the risk assessment process, including: 1) materiality assessment (i.e. determining what risks are likely to be material for a particular sub-sector and geography); 2) the identification of suitable risk indicators and thresholds for different risk levels; and 3) sources of data to assess risk levels. The practicability of assessing natural capital risk in any given sub-sector or geography is therefore dependent on further work to clarify each of these elements.

This paper aims to facilitate progress towards operationalisation (Jax et al., 2018; van Dijk et al., 2018) of the NCRA concept by investigating the extent to which suitable risk indicators,

[1] https://encore.naturalcapital.finance/ (accessed 3 June 2019).

thresholds and data are available to assess material risks in a specific sub-sector and geography: the Australian sheep on-farm production industry. We consider this a 'critical' case (Flyvbjerg, 2006), in the sense that if NCRA is not practicable in this highly favourable context, it is likely to be limited elsewhere. We consider the context favourable as Australia is a developed country that invests a relatively high proportion of GDP into agricultural science and data collection (Heisey and Fuglie, 2018), while also having over A$87 billion of agricultural debt[2] that is highly exposed to a variety of natural capital dependencies.

In contrast to the extensive literature on ecological risk assessment (Suter, 2007), which evaluates the likely impacts *on* the environment of a given activity, there is, as yet, very limited academic literature on the assessment of operational and financial risks *to* an enterprise arising from their impacts and dependencies on natural capital and ecosystem services. Mace et al. (2015) propose the development of risk registers for natural capital assets, which would serve to highlight ecosystem services at highest risk of loss or degradation, while Leach et al. (2019) propose a classification framework for natural capital assets that can underpin corporate natural capital risk assessment; but in both cases the emphasis is on the natural capital assets, rather than the risks to a business. The latter has been explored in case studies on Australian wheat and beef production (Ascui and Cojoianu, 2019b; Cojoianu and Ascui, 2018) on which our analysis builds in two ways: firstly, by investigating the application of NCRA to a different sub-sector (sheep production); and secondly, by conducting a deeper investigation into the availability and adequacy of specific indicators, risk thresholds and data sources to assess the identified risks. The paper is structured as follows: in the next section (2) we outline our research method; section 3 contains our results, summarised in Tables 2 and 3; and in section 4 we discuss our findings and conclusions.

[2] https://www.rba.gov.au/statistics/tables/xls/d09hist.xls (accessed 10 March 2021). Total rural debt, 2020.

2. Method

We define risk as “uncertain consequences, particularly possible exposure to unfavourable consequences” (Hardaker et al., 2015). This definition acknowledges that risks can involve either negative or positive outcomes, although in the context of agricultural lending, banks are primarily interested in understanding the likelihood of negative outcomes. A risk indicator is “something that can be measured, either qualitatively or quantitatively, in order to assess a risk factor”, which in turn is defined as “an element which alone or in combination has the intrinsic potential to give rise to a risk” (Ascui and Cojoianu, 2019a). In order to make practical use of a risk indicator in credit decision-making, some kind of evaluation must be made, comparing the level of risk as measured by the indicator with the level of risk acceptable to the decision-maker – examples include the application of numerical scores or risk exposure statements (e.g. low, medium and high risk) (Coulson, 2002; Mace et al., 2015). Such risk thresholds and evaluations are inherently subjective, but can be facilitated by an understanding of any biophysical indicator-outcome relationship (e.g. whether it is linear, stepped or non-linear), analysis of past outcomes, or benchmarking (e.g. grouping a set of peers into low, medium and high terciles). Finally, we define a data source as a source of quantitative or qualitative information that can enable assessment of a risk indicator against at least a ‘high’ risk threshold.

In order to identify suitable risk indicators, thresholds and data sources for NCRA in Australian sheep production, we first undertook a materiality assessment at the sub-sector level, following the NCFA methodology (Ascui and Cojoianu, 2019a), which in turn is based on the generic assessment methodology of the Natural Capital Protocol (Natural Capital Coalition, 2016). In the absence of any pre-existing natural capital materiality assessment for Australian sheep production, the NCFA taxonomy of potential risks (Ascui and Cojoianu, 2019a) was taken as a starting point, although the possibility of additional risks was also explored.

We focus our analysis on broadacre sheep production, excluding feedlots, which account for about 14% of Australian lamb production (Montossi et al., 2013). In order to simplify our scope, we also exclude irrigated areas, as most Australian sheep production is dependent on rain-fed pastures, fodder crops and stubbles from cereal production. Our analysis is therefore intended to be broadly representative of the majority of Australian sheep production, but it will not necessarily cover all relevant natural capital risks for all parts of the industry in all areas of Australia. Likewise, due to the heterogeneity of the industry across Australia, only a sub-set of the identified risks may be applicable to any specific area.

The analysis was undertaken for both impact and dependency risks. However, this paper covers only the dependency risks. The impact risks for sheep production were found to be similar to the equivalent risks for beef production (Ascui and Cojoianu, 2019b). Impact risks (e.g. risks associated with impacts on biodiversity; greenhouse gas emissions; or contamination and waste) are also generally better understood than dependency risks, and often already addressed through various mechanisms, such as environmental regulations, water and carbon footprints, biodiversity impact assessments and contaminated land assessments (Cambridge Centre for Sustainable Finance, 2016; TEEB, 2012). The impacts of sheep production in Australia are now also self-regulated by a new Sheep Sustainability Framework (2021).

Risks were first defined in terms specific to sheep production, building on related examples (Ascui and Cojoianu, 2019b) and bearing in mind the concept of impact and dependency pathways (Ascui and Cojoianu, 2020; Natural Capital Coalition, 2016). This acknowledges that the risk of adverse operational and financial outcomes for a company, and thus indirectly for a lender or investor, may arise in a variety of different ways (Figure 1), as a result of impacts or dependencies (directly, or indirectly through the company's supply chain). For example, a company may depend on an ecosystem service (such as pollination) which is provided by a stock of natural capital (e.g. a healthy population of bees), which may be threatened by environmental or social changes (such as climate change or the effects of certain agricultural chemicals). The materiality of any given risk is a function of the interactions between all steps in this causal pathway, which we propose can be simplified (for dependency risks) to a combination of the *degree of dependency* and the *severity of threat* (Figure 1). For example, a highly material risk (i.e. something that could significantly affect financial performance) could arise from an increased degree of dependency on a threatened service, or an increased severity of threat to an important dependency. We rated the degree of dependency and the severity of threat separately (low/medium/high, taking into account any mitigating effect of standard industry practices) and combined them according to the matrix in Figure 2.

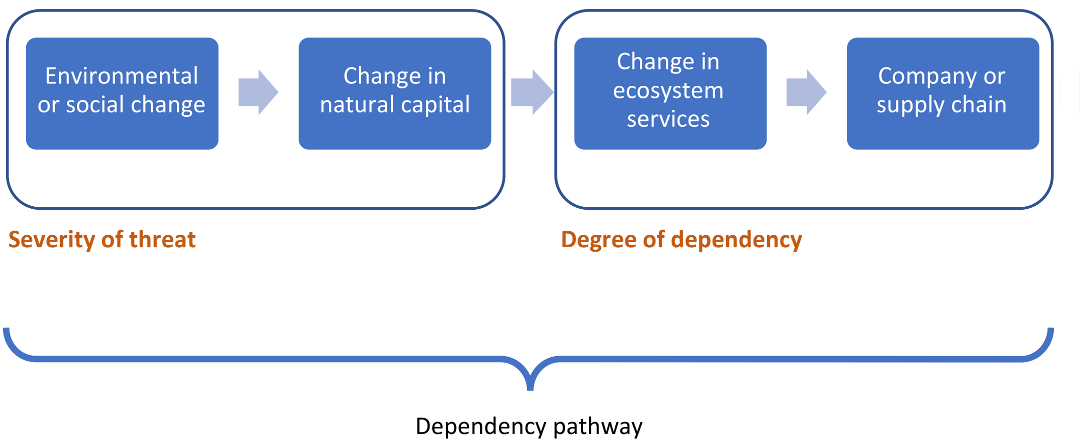

Figure 1: Natural capital dependency pathway and risk materiality. Adapted from Ascui and Cojoianu (2020, p. 124).

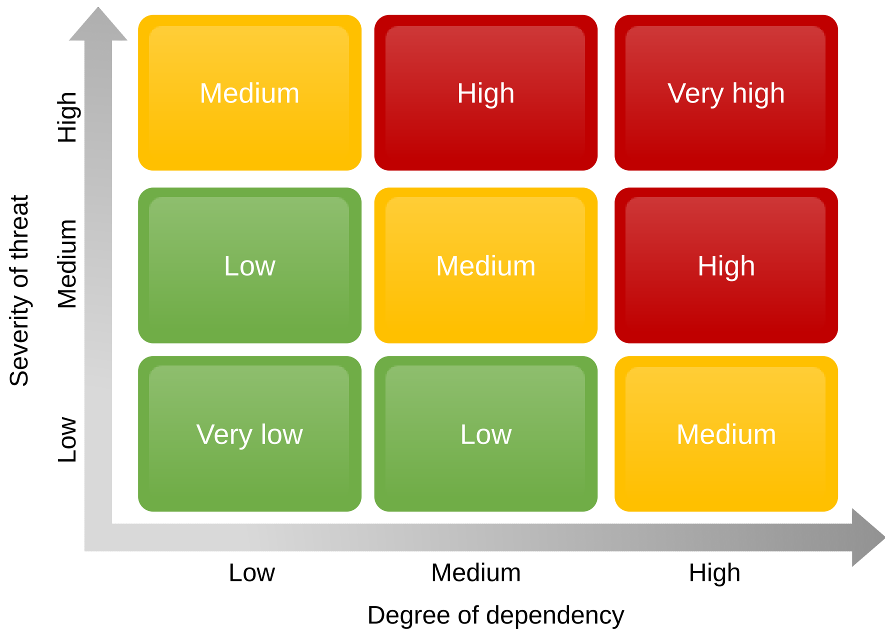

Figure 2: Materiality matrix

The NCFA guide (Ascui and Cojoianu, 2019a) suggests that overall risk should be considered as a product of the current (historical) risk level; the likely future trend over the relevant timescale; the probability of the risk being priced (if relevant); and the producer's ability to mitigate the risk (see Figure 3). We focus our analysis on the indicators, thresholds and sources of data required to assess the current (historical) risk level, as an essential starting point, while acknowledging that further work is required to assess future trends, pricing and risk mitigation, as well as interactions between different risks.

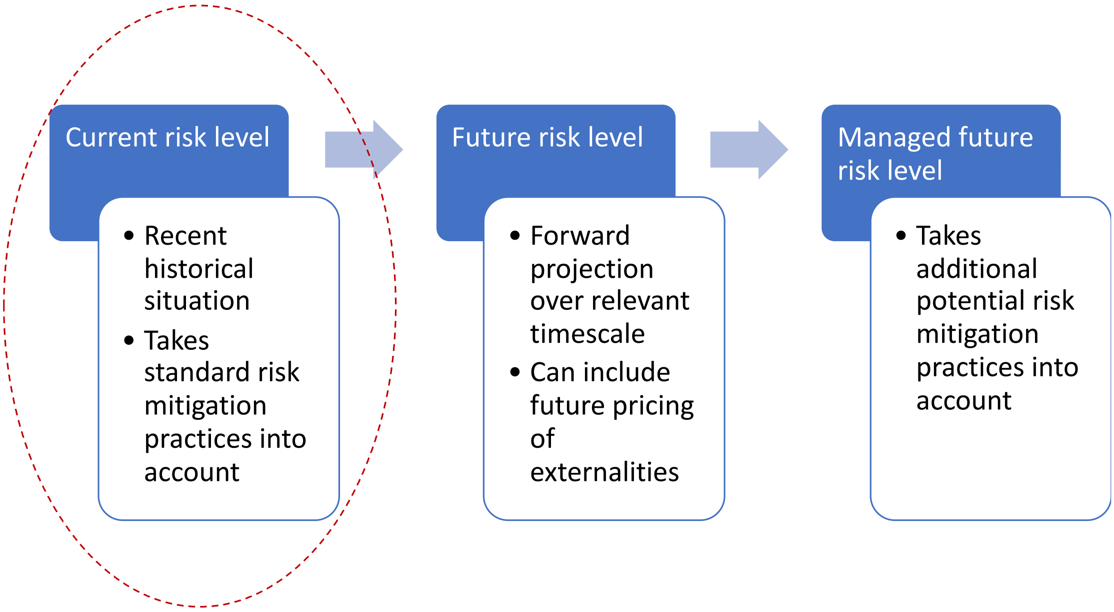

Figure 3: Elements of risk assessment, highlighting our focus on current risk level. Adapted from Ascui and Cojoianu (2019a).

Information on dependencies and threats was triangulated from multiple sources, including a review of academic papers and publications from Australian industry-specific bodies such as Meat and Livestock Australia (MLA), Sheep CRC, Australian Wool Innovation (AWI) and relevant government agencies. Where there was conflicting or unclear evidence of materiality in the literature, the authors reviewed the evidence and made a collective judgement based on their experience (cumulatively around 110 years practical and research involvement, including authorship of 150+ peer reviewed papers in Australian livestock industries, many specifically in sheep production). The literature relating to each risk area was also used to identify potentially suitable risk indicators, thresholds, and sources of data.

In order to assess the practicability of operationalising assessment of a given risk into financial sector decision-making, we used an expert elicitation method (Morgan and Henrion, 1990) to assign a score (on a 5-point Likert scale from 0 to 4, in 0.5 increments) to the indicators and data components, separately. Thresholds were not scored, as in most cases, this would require benchmarking of industry performance against the selected indicators, which does not yet exist. A scoring rubric was used as a guide to aid consistency (Table 1). The indicator score was based on the extent to which an indicator was considered to represent the identified risk. The data score was taken as the level that best represented the most relevant of the four components of reliability, accessibility, coverage and resolution, evaluated on the basis of the situation in 2019. As indicators are of little practical use without data, and vice versa, the minimum of the two scores was taken as the overall practicability score, in preference to alternatives such as a weighted or unweighted average.

Scores were first assigned by each author independently. The initial independent assessment returned relatively highly correlated scores, with average deviation from the mean of 0.50 for indicators and 0.53 for data. Where there were more significant discrepancies (average deviation >1.0) in specific scores, further discussion was held, resulting in a small number of score changes due to sharing of additional information or resolution of differences in interpretation. Additionally, scores for two indicators were reconsidered following comments from an anonymous reviewer. Overall, the average deviation from the mean reduced to 0.46 for both indicators and data, while the highest individual score deviation reduced to 0.75. In other words, on average, scores tended to cluster within the range of a single descriptive 'band' on our scale. We interpret this relatively high degree of inter-rater consistency as demonstrating that the results are reasonably robust despite inevitable differences in interpretation, even between informed experts in a field. The average scores for each component and overall practicability are shown in Table 3 at the end of section 3.

Practicability score	Indicators	Data			
		Reliability	**Accessibility**	**Coverage**	**Resolution**
0 (not applicable)	N/A	N/A			
1 (poor)	Partially or poorly represents the risk	Non-standardised, non-validated; subjectively estimated; high uncertainty	Highly restricted or costly to access; non-digitised (e.g. hand-written logbooks)	Very few regions or producers; <5 years	Regional-scale, e.g. 100x100km
2 (moderate)	Moderately likely to represent the risk	Partly standardised or validated; medium uncertainty	Moderately costly to access; requires specialised software or processing skills	Some regions or producers, c. 10 years	Locality-scale, e.g. 10x10km
3 (good)	Reasonably likely to represent the risk	Standardised or validated; acceptable uncertainty	Minimally costly to access; requires some processing skills	Most regions or producers; c. 20 years	Farm-scale, e.g. 1x1km
4 (excellent)	Highly likely to represent the risk	Standardised, calibrated, rigorously validated; low uncertainty	Freely accessible data; easily searchable online map interface	All regions and producers; 30+ years	Paddock-scale, e.g. 100x100m

Table 1: Scoring rubric

3. Natural capital risks in Australian sheep production

3.1. Case study background – Australian sheep industry

Australia is the world's largest wool producer, accounting for around 24% of world production in 2012 (Cottle et al., 2014), and the world's second-largest producer of lamb and mutton, producing approximately 8% of the world's lamb and mutton supply in 2014.[3] The gross value of lamb and sheep production in Australia was A$4.0 billion in 2017-2018, while wool production accounted for a further A$4.5 billion.[4] There are over 31,000 farms with sheep and lambs in Australia, accounting for 36% of all agricultural businesses in the country.[5] A little over a third of these are specialist sheep producers, while the rest combine sheep farming with other livestock or cropping on mixed farms (Hall et al., 2012).

Apart from certain fleece-shedding breeds, and dairy ewes, the majority of Australian sheep produce two marketable products, wool and meat, and can be farmed with an emphasis on one or the other, or combinations of both. Over the past twenty years, there has been a transition in Australian sheep farming from wool to meat production, accompanied by a decrease of around 40% in the overall sheep flock from 120 million in 2001 to around 70 million in 2010, where it has remained relatively constant through to 2019. Important changes have occurred in the structure of the flock, with an increasing proportion of ewes and a lower percentage of wethers kept for wool production. The increasing proportion of ewes and increased focus on lamb production and reproductive efficiency places more importance on consistent nutrition, thus raising risk during unfavourable seasonal conditions.

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[3] https://www.mla.com.au/globalassets/mla-corporate/prices--markets/documents/trends--analysis/fast-facts--maps/mla_sheep-fast-facts-2017_final.pdf (accessed 19 November 2018).
[4] http://www.abs.gov.au/ausstats/abs@.nsf/0/58529ACD49B5ECE0CA2577A000154456?Opendocument (accessed 18 November 2019).
[5] https://www.mla.com.au/globalassets/mla-corporate/prices--markets/documents/trends--analysis/fast-facts--maps/mla_sheep-fast-facts-2017_final.pdf (accessed 19 November 2018).

3.2. Materiality assessment

Table 2 summarises the results of our assessment of the key natural capital dependency risks likely to have a material impact on sheep production in Australia. The remainder of this section reviews potential indicators, thresholds and data availability for each of the dependency risks assessed as medium or higher materiality, with a focus on assessment of the current (historical) risk level.

Thematic area	Risk area	Dependency risk definition	Materiality	Materiality evidence
Water	Water availability (rainfall)	Insufficient plant available water to produce the feed required to meet livestock grazing needs at the target stocking rate	Very high	In the absence of irrigation, the amount and timing of plant available water derived from rainfall is a key determinant of the growth of pasture, fodder crops and stubbles (Hughes et al., 2011; Kokic et al., 2006) required to meet livestock grazing needs at a given stocking rate, otherwise costly supplementary feeding or de-stocking may be necessary. While animals in good condition can be under-fed for short periods, consistency of nutrition throughout the year is important for general animal welfare, reproductive performance and maintaining consistent wool and lamb quality.[6] Modelling of the effect of the 2018-2019 drought on sheep farm profits estimates a reduction of over 50% from profits under average (1950-1999) climatic conditions (Hughes, 2019). Rainfall in south-western and south-eastern Australia has been declining in recent decades and is projected to decline further in future (CSIRO and Bureau of Meteorology, 2020).
	Water use (livestock drinking water)	Available water supply is insufficient to meet total water demand at the target stocking rate	Very high	Animals cannot survive without sufficient drinking water and it is almost always too expensive to transport off-farm water for livestock consumption. Climate change is likely to reduce the availability of surface water due to declining rainfall and higher temperatures (CSIRO and Bureau of Meteorology, 2020), which in turn is likely to reduce groundwater recharge and hence future groundwater availability, although with varying probabilities across Australia (Barron et al., 2011).
	Water quality	Water is not of sufficient quality to maintain health and/or productivity	High	Sheep can tolerate a range of water quality, but values beyond certain limits can reduce productivity and ultimately render water unusable. Water quality is affected by a wide range of local, regional and global change processes and the state and trend of water quality is highly variable across Australia (Argent, 2016). Climate change may negatively affect water quality by reducing average surface water flows, increasing the incidence of bushfires and heavier rainstorms resulting in higher surface run-off, and increasing water temperatures, leading to increased frequency of algal blooms (CSIRO and Bureau of Meteorology, 2020; Soh et al., 2008).
Weather and climate	Temperature extremes	Mortality, lower productivity and/or increased costs due to exposure to temperature extremes	High	Sheep can be affected by both heat and cold stress. Heat stress is a significant factor in reproductive performance, reducing ram fertility and foetal growth rates in pregnant ewes under continuously hot conditions (Harle et al., 2007). Cold stress at lambing and immediately after shearing can have a significant impact on mortality rates (Alexander and Williams, 1971; Collier and Collier, 2012; Donnelly, 1984). For example, 100,000 recently shorn sheep died as a result of a surprise chill event in south-western Victoria in December 1987 (Weeks et al., 2015). Climate change is broadly expected to reduce cold stress and increase heat stress

[6] https://www.wool.com/market-intelligence/woolcheque/wool-characteristics/diameter/ (accessed 29 November 2018).

				(CSIRO and Bureau of Meteorology, 2020), but may also increase variability in the range of temperature extremes. For example, despite the warming trend in average minimum temperatures, parts of southern Australia have experienced increased frost frequency in recent decades and cold stress risk may remain largely unchanged in these regions for the next few decades (Crimp et al., 2019, 2016).
	Extreme weather	Mortality, lower productivity and/or increased costs due to exposure to extreme weather events	Very high	Drought is covered under water availability (see section 3.3) and heatwaves can likewise considered under temperature extremes (section 3.6). The remaining extreme weather events with the greatest risk of impact on sheep production in Australia are bushfires, floods and storms, which have the potential to cause mass mortality as well as lower productivity due to loss of pasture and health impacts. Climate change is likely to lead to an increase in fire weather, the proportion of high-intensity storms and the intensity of heavy rainfall events (CSIRO and Bureau of Meteorology, 2020).
Soil	Soil quality	Lower productivity due to poor soil quality	High	Although soil quality is acknowledged as a major determinant of agricultural productivity, change is usually relatively slow (except in the case of erosion, where damage from wind and water can be rapid and serious). Climate change is likely to lead to an increase in wind and water erosion as a result of the higher intensity of storms and heavy rainfall events (CSIRO and Bureau of Meteorology, 2020).
	Fertiliser use	Lower productivity due to deficiency of key nutrients	Medium	In Australian sheep production, fertiliser is generally only used on farms in the sheep-wheat and high rainfall zones, where it accounts on average for 14% and 10% of total farm cash costs, respectively (compared with <2% for farms in the pastoral zone).[7] Fertiliser is largely derived from non-renewable natural capital resources that may be less available or more expensive in future: for example, the cost of phosphorus-based fertilisers, the main type used in Australian sheep production (Cottle et al., 2016; Wiedemann et al., 2016), doubled over the decade 2000-2010 due to the depletion of low-cost reserves (Simpson et al., 2010).
Biodiversity and ecosystems	Biodiversity	Ecosystem services provided by biodiversity become unavailable	Low	Biodiversity provides ecosystem services related to pasture composition (section 3.10) and soil quality (section 3.8), and can provide some protection against ecosystem disservices from weeds, pests and diseases (sections 3.11 and 3.12). Although some sheep production depends on insect pollination (pastures with a high content of clovers or other legumes), the possibility of substitution between different pasture types suggests that this risk is likely to have relatively low materiality for Australian sheep production. Pollinator populations have declined significantly in many countries in recent decades (TEEB, 2012).
	Pasture composition	Lower productivity and/or increased costs due to loss of optimal pasture composition	High	Different pasture types and species have different performance characteristics, such as perennial grasses being able to utilise more water for growth over a longer growing season (Mason et al., 2003), while the percentage of legumes is a key factor driving animal

[7] Calculated as the average from 2006-2007 to 2016-2017. Data from http://apps.agriculture.gov.au/mla/mla.asp (accessed 11 December 2018).

				productivity in southern Australian grazing systems (Graham et al., 2003). Pasture composition is strongly affected by management practices, while climate change is also shifting optimal climatic zones poleward for many species (IPCC, 2019).
	Weeds	Lower productivity and/or increased costs due to weeds, pests or diseases	High	Weeds pose a significant risk to Australian sheep production, estimated to cause total economic losses to the sheep meat and wool industries of A$283 and A$588 million, or 11% and 17% of the gross value of production for these sectors, respectively (Jones and Sinden, 2006). The severity of threat from weeds is uncertain as it depends on complex interactions between social factors such as biosecurity practices, and various environmental factors. Climate change is expected to change the geographic range of weed species, while elevated CO_2 levels can affect yield losses and herbicide efficacy (Porter et al., 2014).
	Pests and diseases		High	Pests and diseases are significant risks for Australian sheep production, with the top 23 endemic pests and diseases in Australian sheep production estimated to cost the industry over $2 billion per annum (GHD, 2015). The severity of threat from pests and diseases is uncertain, as for weeds above.
	Animal welfare	Lower productivity and/or legal, regulatory or reputational costs due to poor animal welfare	Medium	Poor animal welfare is associated with increased mortality, poorer health, poorer product quality, reduced prices and/or market access, and lower farmer satisfaction (Dawkins, 2017; Montossi et al., 2013). Adherence to Australian standards (Animal Health Australia, 2016) should minimise these risks.
Energy	Energy use	Higher costs due to inefficient use of energy and/or higher prices of energy inputs	Very low	Wiedemann et al. (2016) estimate total fossil-fuel energy demand for a range of Australian sheep farms to be 2.5-7 MJ/kg LW, considered to be low to moderate, in comparison with other agricultural systems. Fuel costs for sheep meat producers averaged under A$0.10/kg LW in 2016-2017, or about 3% of total costs.[8] Energy use is therefore not considered to be a material natural capital dependency risk for Australian sheep production (except for feedlots, which are excluded from our analysis).

Table 2: Natural capital risk materiality assessment for Australian sheep production. refers to degree of dependency and to severity of threat (green = low, orange = medium, red = high).

[8] http://www.agriculture.gov.au/abares/research-topics/surveys/lamb#detailed-cost-of-production-findings (accessed 4 January 2019).

3.3. Water availability (rainfall)

We divide the category of 'water availability' risk (Ascui and Cojoianu, 2019b, 2019a) into availability of on-farm rainfall, considered in this section, and the risks associated with dependency on surface or sub-surface water for livestock drinking supply, considered in section 3.4. We acknowledge a separate category of risks associated with availability of water supplies for irrigation, which is excluded from our analysis.

Indicators: Measuring rainwater availability risk for livestock production is challenging, since the level of risk depends on complex interactions between the quantity and timing of rainfall, its conversion to plant available water, pasture growth, livestock feed demand, and management decisions, in particular the stocking rate. This can be contrasted with the equivalent risk for a rain-fed crop such as wheat, where rainfall and yield tend to be directly correlated (French and Schultz, 1984). There is therefore a range of choices available, from simple benchmarks which are unlikely fully to capture these complexities (score 2.9), through to the use of sophisticated modelling (score 3.6).

A widely used heuristic in Australian sheep production is a maximum potential yield benchmark of 1.3 dry sheep equivalent (DSE)/ha for every 25mm of annual rainfall over 250mm (French, 1987). Farms with a target stocking rate higher than this benchmark could indicate a high-risk stocking strategy; while lower figures could suggest a conservative approach, possibly at the expense of financial returns. However, the comparability of stocking rates is complicated by variable use of supplementary feeds. Farms which were otherwise identical could also sustain different stocking rates if they had different soil condition, pasture composition, sheep genetics, or grazing management. Further research is required to compare the French (1987) benchmark with alternatives, for example based on growing season rainfall (Bolger and Turner, 1999) or length of growing season (Sanford et al., 2003); and to investigate the correlation of each of these with financial performance.

Differences in reliability of rainfall could also make a substantial difference in risk between two farms with otherwise identical average rainfall. This could be addressed with a rainfall variability index, such as that published by the Australian Bureau of Meteorology (BoM), where index values over 1.25 are considered 'high'.[9] Again, further research is required to investigate the correlation of such indices with financial performance.

Alternatively, a more sophisticated assessment of rainwater availability risk could be derived from a biophysical model for livestock production, using farm-specific inputs. One example is Ag360 (formerly known as ASKBILL), which develops pasture availability profiles for specific areas based on user input of property-specific data (Kahn et al., 2017).[10] The model incorporates 30 years of historical Australian meteorological data, which could be used to evaluate the probability, based on historical rainfall patterns, of pasture growth being insufficient to meet target weight and condition for the defined stock of animals. The model is proprietary, but inexpensive to access.

Data: Data to calculate the above indicators is readily available in Australia (score 3.1 for benchmarks and 3.4 for modelling). For example, historical daily rainfall data is available for the entire country (at a resolution of approximately 5x5km), for any period from 1900 to the present, from the BoM.[11] Data on target stocking rate would be readily available from the producer. A modelling approach would require more farm-specific data to be provided by the

[9] http://www.bom.gov.au/jsp/ncc/climate_averages/rainfall-variability/index.jsp (accessed 28 November 2018).
[10] https://ag360.com.au/ (accessed 17 March 2021).
[11] http://www.bom.gov.au/climate/how/newproducts/IDCdrgrids.shtml (accessed 2 May 2019).

producer, but this is realistic for a decision-support tool such as Ag360 that is already in use by the industry.

3.4. Water use

This section concerns the use of water for stock drinking purposes, being the main consumptive use of water on sheep farms (excluding irrigation).

Indicators: Ascui and Cojoianu (2019a) suggest that average total water consumption (including losses) per DSE could provide an indicator of exposure to this risk (score 2.5). However, the rate of consumption should ideally be compared with the available water supply, which is difficult to assess as it will depend on the local supply context. Alternatively, a risk assessment could be based solely on the trend in availability of the water resource (score 2.9 for groundwater and 3.0 for surface water).

Data: Lookup tables exist which characterise average daily water consumption per DSE for different parts of Australia (Luke, 1987), but these estimates do not include losses (score 2.6). At present, it is unlikely that many producers could provide robust measured data on water use, but this may change in the near future, with deployment of lower-cost in-field sensors and/or remote sensing (Murray-Darling Basin Authority, 2018).[12] In terms of resource trends, information on 5-, 10- and 20-year groundwater level trends in the area can be obtained from the BoM's Australian Groundwater Insight tool (score 2.3).[13] Similarly, for surface water, the Bureau's Regional Water Information tool provides an analysis of the trend in the lowest 10% streamflows since 1975, by river region (score 2.4).[14]

[12] For examples of in-field water sensors, see https://www.goannaag.com.au/solutions/gosense (accessed 20 November 2019).
[13] http://www.bom.gov.au/water/groundwater/insight/#/gwtrend/summary (accessed 25 June 2019).
[14] http://www.bom.gov.au/water/rwi/#sf_trlf/ (accessed 25 June 2019).

3.5. Water quality

Indicators: Water quality risk could be evaluated according to the frequency of past episodes of poor stock drinking water quality (score 2.6), if a water quality monitoring programme is in place (Ascui and Cojoianu, 2019b), or according to the trend in one or more water quality indicators such as groundwater salinity (score 3.0) or surface water quality parameters (score 2.4). Thresholds for frequency of past episodes would need to be established, for example by reference to standards or benchmarking against comparable peers, whereas specific water quality indicators usually have well-defined tolerability thresholds (ANZECC and ARMCANZ, 2000).

Data: Farm-specific water quality data is unlikely to be available for the majority of producers (score 2.1), with the possible exception of producers who are primarily reliant on groundwater resources. Data on average salinity of groundwater aquifers, and the trend in salinity change, is available from the BoM's Groundwater Insight tool (score 3.0).[15] Surface water quality monitoring in Australia is carried out by a range of different government and non-government agencies, making comparative assessment very challenging (Argent, 2016). In recent years, historical data from several thousand surface water quality monitoring stations across Australia has been collated by the BoM, and presented in a searchable online map database.[16] Data is available on the following parameters relevant to water quality: pH, electrical conductivity (an indicator of salinity), turbidity and temperature. Temporal and spatial coverage is still limited, however, and interpreting this data presents significant further challenges (score 2.0). Remote sensing can identify certain water quality issues such as algal

[15] http://www.bom.gov.au/water/groundwater/insight/#/salinity (accessed 26 June 2019).
[16] http://www.bom.gov.au/waterdata/ (accessed 26 June 2019).

blooms and turbidity, and a pilot project has been developed to provide historical data on this for the state of New South Wales.[17]

3.6. Temperature extremes

Indicators: The risk of exposure to heat and cold stress depends on various factors including air temperature, humidity/rainfall, wind speeds, solar radiation, animal characteristics, condition and both quantity and quality of feed and water (Ascui and Cojoianu, 2019b), and a variety of risk metrics exist. For example, Weeks *et al.* (2015) calculate a sheep chill index based on temperature, wind speed and accumulated 24-hour rainfall, with chill rates over 1,000 kJ/m^2/hour being considered high risk. Similarly, Agriculture Victoria has experimented with calculating a Heat Load Index (Wang et al., 2018) based on solar radiation, air temperature, wind speed at sheep height and humidity, with values over 77 indicating hot and over 86 very hot conditions.[18] One way of comparing producers would be to calculate the long-term average number of days over a threshold beyond which the risk of severe impacts is high ('stress days') (score 3.1). Nevertheless, while stress days could provide a way of comparing different producers, further work is required to determine the number of stress days considered to represent different levels of risk.

Data: In principle, it should be possible to obtain the necessary historical meteorological data to calculate sheep-specific chill and heat indices from the BoM (score 3.4), but to the best of our knowledge, historical index data is currently only available via third-party providers such as Ag360 (Kahn et al., 2017).

[17] https://ecos.csiro.au/algal-blooms/ (accessed 29 November 2019).
[18] http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/ibaw (accessed 30 November 2018).

3.7. Extreme weather

Indicators: Ascui and Cojoianu (2019a) suggest that extreme weather risks could be evaluated by drawing on historical data on the frequency, severity and duration of extreme weather events. The insurance industry has long experience of defining risk thresholds in relation to extreme weather events (score 2.9).

Data: In Australia, address-level estimates of exposures to flood, storm tide, extreme rainfall, cyclone, lightning, bushfire and hail events are available from the Insurance Council of Australia (ICA).[19] Satellite observations of the physical presence of water on land, from which flood events can be inferred, are available for the whole of Australia from 1987 onwards via the Water Observations from Space dataset,[20] used by Hughes, Lawson and Valle (2017) to calculate the average frequency of farm flooding. A variety of publicly available flood records and studies on flood risk are available from the Australian Flood Risk Information Portal.[21] Overall, it seems feasible to obtain farm-level estimates of extreme weather risks from these sources (score 2.9).

3.8. Soil quality

Indicators: Ascui and Cojoianu (2019a) propose that key soil quality risk indicators should include soil acidity, soil organic carbon (SOC), salinity, and water and wind erosion; noting that physical and biological soil condition are also relevant but difficult to monitor at scale, while soil nutrients are partially addressed in relation to the use of fertilisers to correct for nutrient deficiencies (section 3.9).

[19] See http://www.icadataglobe.com/ (accessed 14 May 2019).
[20] See https://www.ga.gov.au/scientific-topics/community-safety/flood/wofs (accessed 13 May 2019).
[21] http://www.ga.gov.au/scientific-topics/hazards/flood/afrip (accessed 13 May 2019).

The proportion of the farm's usable area with a pH lower than 4.7 in $CaCl_2$ in the top 15cm could be used as an indicator of the current level of acidification risk (score 3.0), as this level is generally considered to be problematic, although some pasture species can tolerate slightly more acidic levels.[22] Similarly, the proportions of the farm's usable area with SOC lower than 2% and 1% could be used as indicators of soil organic carbon risk (score 3.4), as yield penalties tend to be greatest below these thresholds (Oldfield et al., 2019). A similar approach can be taken with salinity (the proportion of the farm's usable area with soil in high to extremely saline condition), although interpretation of the most commonly used metric (electrical conductivity) depends on the soil type (score 3.3).

Water and wind erosion risk is determined by multiple factors. However, low levels of ground cover leave the soil exposed to both erosion mechanisms, with erosion more likely to occur when ground cover is <50%, and minimised when ground cover is >70%.[23] The proportions of the farm's usable area with <70% and <50% minimum ground cover (at any time over the past 5-10 years, to capture inter-annual variability) could therefore be used as indicators of the current level of erosion risk (score 3.9). For all of the above soil indicators, risk thresholds for proportions of the farm's usable area falling into each category would need to be determined, for example by benchmarking against comparable peers.

Data: Soil quality data has not been systematically collected across Australia, resulting in a patchwork of incomplete data resulting from different assessment programmes. Nevertheless, a publicly accessible central repository of soil data exists: the Australian Soil Resource Information System (ASRIS).[24] Around 70% of Australia's rangelands are covered by

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[22] See http://www.makingmorefromsheep.com.au/healthy-soils/tool_6.5.htm (accessed 15 August 2018).
[23] https://www.mla.com.au/research-and-development/Environment-sustainability/Sustainable-grazing-a-producer-resource/climate-variability-using-water-wisely/maintain-ground-cover/ (accessed 15 August 2018).
[24] http://www.asris.csiro.au/ (accessed 14 May 2019).

some data at the 'district' level, with a resolution of 1km; more detailed mapping at 300m resolution is only available for less than 5% of rangelands.[25] In 2014, the Soil and Landscape Grid of Australia (SLGA) was launched, combining soil monitoring data with new spatial modelling to generate inferred soil attribute maps at 90x90m resolution for the entire country (Grundy et al., 2015). The results can be viewed via a map interface or downloaded in a variety of data formats.[26] Both ASRIS and the SLGA provide estimates of soil acidity (pH, in $CaCl_2$) and SOC at different soil depths (score 2.3 and 2.1, respectively). Electrical conductivity data is provided only in ASRIS, which also provides soil type information (score 2.4). Satellite-derived ground cover data for Australia can be obtained from the Ground Cover Monitoring for Australia project, and viewed through the Rangelands and Pasture Productivity (RAPP) online mapping interface, or downloaded in various formats from the Terrestrial Ecosystem Research Network (TERN) (score 3.4).[27]

3.9. Fertiliser use

Indicators: The main type of fertiliser used in Australian sheep production is phosphorus (P) based, typically applied in the form of single superphosphate (Cottle et al., 2016; Wiedemann et al., 2016), although mixed farms in the sheep-wheat zone also tend to use nitrogen-based fertiliser during the cropping phase. Ascui and Cojoianu (2019a) suggest measuring the quantity and cost of fertiliser used, by type, as indicators of dependencies associated with fertiliser use (score 3.0). In order for this to be comparable across producers, the quantity and cost (averaged over several years) would need to be normalised, for example per hectare, DSE, kg live weight (LW) or kg clean fleece weight (CFW), with risk thresholds determined by benchmarking against peers. An alternative approach could be to 'stress test' the impact of an increase in fertiliser price on total farm cash costs, for example using the price spike

[25] http://www.asris.csiro.au/methods.html#ASRIS_Levels (accessed 14 May 2019).
[26] http://www.clw.csiro.au/aclep/soillandscapegrid/index.html (accessed 26 June 2019).
[27] https://www.agriculture.gov.au/abares/aclump/land-cover/ground-cover-monitoring-for-australia and https://www.tern.org.au/ (accessed 25 May 2021).

experienced in most fertilisers in 2008 (Wong et al., 2012), and comparing the results with long-term or more recent averages for the zone (score 2.6).

Data: Producer records would be required to measure the quantity of fertiliser used (score 3.0). Cost data could also be obtained from the producer, or from price projections published by reputable market analysts (score 3.1).

3.10. Pasture composition

Indicators: Different grazing systems, soils and climatic conditions favour different combinations of legumes, annual and perennial grasses. Ascui and Cojoianu (2019a) note that pasture composition is usually evaluated by on-site visual assessment, and suggest that a more practical proxy measure of pasture composition risk could be the proportion of a farm in 'C' or 'D' condition according to the 'ABCD' standardised qualitative method for categorising land grazing condition (Chilcott et al., 2003). 'A' condition includes having a high density and coverage of '3P' (palatable, productive and perennial) grasses while 'D' condition is characterised by a general lack of perennial grasses or forbs and high numbers of weeds. Risk thresholds in terms of percentages of farm grazing land in 'C' or 'D' condition would need to be established by benchmarking against peers. It should be noted that the ABCD system is only applicable to native pastures in parts of northern Australia at present, and requires further development to apply to other regions and pasture types (score 2.5).[28]

Data: ABCD land condition could be assessed by the producer or a third party using visual assessment, or a modelled estimate can be obtained from Digital Agricultural Services (DAS), a proprietary service provider (score 2.3).[29]

[28] We thank an anonymous reviewer for pointing out these limitations.
[29] https://digitalagricultureservices.com/ (accessed 27 August 2018).

3.11. Weeds

Indicators: The risk of reduced profitability due to weed infestations is a function of exposure (the probability that an area will be exposed to weed seeds, or other means of transmission), susceptibility (the area's vulnerability to weed establishment) and the level of threat posed by the weed in question. Exposure can be assessed according to whether a property is within the current or projected distribution of a weed (score 3.1). However, a major challenge to using exposure as a risk indicator is the number and geographic diversity of relevant weeds: Grice *et al.* (2014) identify 71 widespread and 18 emerging weeds of significance to Australian livestock industries.

An alternative is to focus on susceptibility, as there are generic land conditions that favour establishment of most (but not all) weed species. Ascui and Cojoianu (2019a) suggest that, as for pasture composition (section 3.10), the proportion of a farm in 'C' or 'D' condition could be used as a proxy for weed risk (score 2.9). 'C' condition typically includes the obvious presence of weeds and >50% bare ground at the end of the growing season, while 'D' lands typically have weed infestations covering significant areas, severe erosion and large bare areas (Karfs et al., 2009; Pettit, 2011). Alternatively, the farm's proportion of bare and/or broken ground (measured as zero ground cover) could be used as a proxy indicator (score 3.3).

Data: Aside from the coordinated national response to Weeds of National Significance[30] (32 weeds classified as such, based on their invasiveness, potential for spread and environmental, social and economic impacts), there is little harmonisation in weed management across Australia (Cattanach et al., 2013). Noxious weeds are defined in legislation by each state and territory, and surveillance is likewise conducted by various bodies at different levels. Some

[30] http://www.environment.gov.au/biodiversity/invasive/weeds/weeds/lists/wons.html (accessed 2 January 2019).

(but not all) Australian states provide maps showing the current and projected future distribution of certain weed species (score 2.4).[31] Producer records could also provide information on weed species, and there is some potential for identification of certain weed species from satellite- or drone-based remote sensing. Data sources for ABCD land condition (score 3.0) and ground cover data sources (score 3.1) are discussed in sections 3.10 and 3.8, respectively.

3.12. Pests and diseases

Indicators: Ascui and Cojoianu (2019a) suggest that the current level of pest and disease risk could be evaluated by reference to historical incidence levels, preferably disaggregated by individual pest/disease and benchmarked against similar peers or industry benchmarks, with data sourced from producer and/or processor records (score 2.6). An example of an industry-wide benchmark would be 2% of animals struck by flies in a typical year (Sheep CRC, 2018); predation by feral animals such as pigs, foxes and wild dogs can also be compared against national benchmarks. An additional proxy indicator could be whether or not the farm has a documented biosecurity plan (score 2.9).

Data: Animal Health Australia collects data on 20 significant pests, diseases and other animal health conditions from 14 domestic and export processing plants across Australia under the National Sheep Health Monitoring Project, and curates a national database (the Endemic Disease Information System).[32] However, this only provides partial coverage (e.g. 10% of total national slaughter in 2015 – Bryan et al., 2016). Otherwise, historical incidence data could be sourced from the producer, or potentially from processors (score 2.0).

[31] See for example http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/lwm_invasive-plants_common-name (accessed 24 January 2020).
[32] https://www.animalhealthaustralia.com.au/nshmp/ (accessed 3 January 2019).

Evidence for documented biosecurity plans could be obtained from producers, noting that a number of voluntary accreditation schemes in Australia include requirements on biosecurity practices and monitoring (score 2.9).[33] Farms which have signed up to the voluntary Ovine Johne's Disease Market Assurance Program (MAP) must also have implemented a biosecurity plan, and are listed on the Australian MAP register.[34]

3.13. Animal welfare

Indicators: Ascui and Cojoianu (2019a) suggest that animal welfare risk could be evaluated by reference to documented compliance with relevant animal welfare standards (score 3.3). Relevant standards for Australian sheep production include the mandatory Australian Animal Welfare Standards and Guidelines for Sheep (Animal Health Australia, 2016) and voluntary standards such as the MLA Livestock Production Assurance (LPA) scheme,[35] the Responsible Wool Standard (Textile Exchange, 2016) and SustainaWool (New England Wool, 2017). In addition, mortality rates provide an indicator of the state of animal welfare (score 3.6). In terms of thresholds, maximum pre-weaning loss targets of 10% for single-born and 30% for twin-born Merino lambs have been proposed (Hinch and Brien, 2014). For weaners, it has been suggested that over 4% mortality should be considered 'high', although this rate was exceeded by 44% of farms, and 14% reported rates over 10% (Campbell et al., 2014).

Data: Data on welfare compliance and mortality rates would need to be obtained from producers (score 2.3 and 2.9, respectively).

[33] See https://www.mla.com.au/meat-safety-and-traceability/red-meat-integrity-system/about-the-livestock-production-assurance-program/ and http://jbssa.com.au/OurCompany/OurQualityPromise/JBSFarmAssurance/default.aspx (accessed 3 January 2019).
[34] https://edis.animalhealthaustralia.com.au/public.php?page=mapsearch&aha_program=3 (accessed 3 January 2019).
[35] https://www.mla.com.au/meat-safety-and-traceability/red-meat-integrity-system/about-the-livestock-production-assurance-program/ (accessed 3 January 2019).

3.14. Summary

Table 3 below summarises potential indicators, thresholds and data sources for each of the identified risks.

Thematic area	Risk area	Potential indicators	Example thresholds	Example data sources	Average indicator score	Average data score	Overall score
Water	Water availability (rainfall)	Stocking rate index (e.g. stocking rate (DSE/ha) per 25mm long-term average annual rainfall over 250mm)	>1.3 high	Historical rainfall amount: BoM; Stocking rate: producer	2.9	3.1	2.9
		Long-term annual rainfall variability index	>1.25 high	BoM	2.9	3.1	2.9
		Modelled probability of pasture growth being insufficient to meet target needs	Tbd	Ag360; Producer	3.6	3.4	3.4
	Water use	Average total water consumption per DSE	> average consumption per DSE: high; total water consumption thresholds tbd	Producer	2.5	2.6	2.5
		Groundwater: 20-year groundwater level trend	Declining: high	BoM	2.9	2.3	2.3
		Surface water: Trend in lowest 10% streamflows	Declining: high	BoM	3.0	2.4	2.4
	Water quality	Frequency of poor stock drinking water quality episodes	Tbd	Producer	2.6	2.1	2.1
		Groundwater salinity (average and trend)	Average 1,000-3,000 mg/L TDS increasing: high; Average <1,000 mg/L TDS increasing: medium	BoM	3.0	3.4	3.0
		Surface water quality	Tbd	BoM	2.4	2.0	2.0
Weather and climate	Temperature extremes	Long-term average number of days over 1,000 kJ/m²/hour (cold stress) or Heat Load Index over 77 (heat stress)	Tbd	BoM	3.1	3.4	3.1
	Extreme weather	Historical frequency, severity and duration of extreme weather events	As defined by insurance industry	Insurance Council of Australia; Australian Flood Risk Information Portal	2.9	2.9	2.9
Soil	Soil quality	Proportion of farm's usable area with pH<4.7 (in $CaCl_2$) in top 15cm	Tbd	ASRIS/SLGA	3.0	2.3	2.3
		Proportion of farm's usable area with SOC <2% and 1% in top 15cm	Tbd	ASRIS/SLGA	3.4	2.1	2.1
		Proportion of farm's usable area in high to extremely saline condition	Tbd	ASRIS	3.3	2.4	2.4
		Proportion of farm's usable area with minimum ground cover <70% and <50%	Tbd	RAPP; TERN	3.9	3.4	3.4

	Fertiliser use	Average quantity and cost of fertiliser used, by type, per ha, DSE, kg LW or kg CFW	Tbd	Producer; Market analysts; Historical prices	3.0	3.0	3.0
		'Stress test' impact of high fertiliser price on total farm cash costs	Tbd	Producer; Market analysts; Historical prices	2.6	3.1	2.6
Biodiversity and ecosystems	Biodiversity	N/A	N/A	N/A	N/A	N/A	N/A
	Pasture composition	Proportion of farm grazing land in 'C' or 'D' condition	Tbd	Producer; Site assessment; DAS	2.5	2.3	2.3
	Weeds	Exposure to grazing-relevant weeds	Present: high; within projected distribution: medium; outside projected distribution: low	State and territory weed distribution maps	3.1	2.4	2.4
		Proportion of farm grazing land in 'C' or 'D' condition	Tbd	Producer; Site assessment; DAS	2.5	2.3	2.3
		Proportion of farm grazing land with bare and/or broken ground (zero ground cover)	Tbd	RAPP; TERN	3.3	3.1	3.1
	Pests and diseases	Historical frequency and severity of pests and diseases outbreaks	Tbd	Producer; Processors; Animal Health Australia	2.6	2.0	2.0
		Quality of biosecurity management	Lack of biosecurity management plan or certification: medium to high	Producer; Third-party assurance schemes	2.9	2.9	2.9
	Animal welfare	Historical level of non-compliance with animal welfare standards	Tbd	Producer	3.3	2.3	2.3
		Historical mortality rates (% lambs, weaners, ewes)	Single-born lambs: >10% high; Twin-born lambs: >30% high; Weaners: >4% medium, >10% high; Ewes: tbd	Producer	3.6	2.9	2.9
Energy	Energy use	N/A	N/A	N/A	N/A	N/A	N/A

Tbd: To be determined, for example by benchmarking against peers

Table 3: Practicability assessment for Australian sheep production natural capital risk indicators, thresholds and data

4. Discussion and conclusions

A lender considering an application for credit from an agricultural producer must make a decision, despite numerous sources of uncertainty about the producer's ability to repay the debt. If the uncertainty, or risk, is well understood, it can be precisely incorporated into loan pricing as a risk premium, thus ensuring an adequate return on capital in aggregate across a portfolio of loans. If the risk is not well understood, then the risk premium may be set too low, exposing the lender to net loss across the portfolio; or too high, thus imposing higher costs on borrowers and restricting the supply of finance for much-needed investments in sustainable intensification. Both of these latter outcomes are sub-optimal. Understanding risk is therefore of vital importance for the lender, as well as the producer, and the future trajectory of agricultural systems.

Natural capital risks are an important component of agricultural risk, along with other factors such as fluctuations in prices for inputs and outputs, regulatory or political risk, and human risks associated with farm management (Hardaker et al., 2015). Yet current credit decision-making practice in the agricultural sector relies primarily on review of the producer's recent financial records and the lender's assessment of management capability, largely ignoring natural capital risks.[36] Leading financial institutions now appreciate that they are exposed to natural capital risks, and that they need to improve their understanding of these risks (Henry, 2016; NAB, 2018; Natural Capital Declaration, 2012). Progress has been made in developing natural capital risk assessment methodologies and tools (Ascui and Cojoianu, 2019a; Natural Capital Coalition, 2018, 2016; NCFA and PwC, 2018).[37] At the level of individual transactions such as a loan to purchase agricultural land, however, it remains unclear what risks are

[36] Personal communication, Agribusiness finance manager, August 12, 2016.
[37] https://encore.naturalcapital.finance/ (accessed 3 June 2019).

material and how they could be measured. Our assessment of Australian sheep production is intended to investigate whether NCRA is practicable, in a best-case scenario of a developed country with a strong agricultural science base and high exposure to natural capital risks.

Our materiality assessment shows that the natural capital risks of likely materiality for Australian sheep production are similar to those for Australian beef production (Ascui and Cojoianu, 2019b), which is not surprising given the substantial geographical overlap and biophysical similarities between the two livestock systems. Nevertheless, there are minor differences, such as the greater vulnerability of lambs to cold exposure, which should not be overlooked.

Our detailed analysis of the feasibility of assessing natural capital dependency risks for Australian sheep production found that at least moderately practicable indicators and data exist to assess all of the 11 identified risks with medium or higher materiality. Of the 26 potentially feasible indicators evaluated, 14 were considered to have good and 12 to have moderate overall practicability. The limiting factor in most (20) cases was availability of suitable data, as opposed to the effectiveness of the indicator (6). The lowest-scoring indicators were 'Surface water quality' and 'Historical frequency and severity of pests and diseases outbreaks', both of which were considered moderately practicable as indicators (scores 2.4 and 2.6), but with limited available data (score 2.0). The highest-scoring indicators were 'Modelled probability of pasture growth being insufficient to meet target needs' and 'Proportion of farm's usable area with minimum ground cover <70% and <50%', both with overall scores of 3.4. This is encouraging, given that achieving sustainable stocking rates is a pre-eminent challenge for pastoral enterprises (Mason et al., 2003; O'Reagain et al., 2014), and over-grazing, leading to depleted ground cover, is one of the main risks that can significantly reduce soil natural capital value. While these conclusions apply only to Australian sheep production, the similarities in material risks and physical overlaps with broadacre cropping (such as wheat) and beef production in Australia (Ascui and Cojoianu, 2019b; Cojoianu and Ascui, 2018) suggest that NCRA is likely to be similarly practicable for these sectors, which (with sheep production) amount to approximately 44% of the gross value of Australian agricultural production in 2017-2018.[38] Further research is required to investigate the practicability of NCRA in other sub-sectors and geographies.

The principal remaining challenge is the identification of suitable risk thresholds, which at this point could only be characterised for a few of the indicators. This is a generic challenge for natural capital and ecosystem services assessment (Smith et al., 2017). Some indicators are associated with clear biophysical thresholds, whereas others would require benchmarking or further research on the relationship between the indicator and farm financial performance – for example, using historical datasets to back-test indicator performance. The level of risk that a lender is willing to accept is ultimately a decision for each lender, but scientific inquiry can assist in providing the evidence base to support such judgements. The fact that determining suitable indicators for natural capital risks is not an exact science (Lien et al., 2007) should not overshadow the point that current credit decision-making practice is also based on imperfect indicators and data: past financial performance is never a guarantee of future financial performance, and agricultural production is characteristically volatile over a range of time periods. The possibility of perverse incentives arising from attention to natural capital risk indicators should also be investigated, while recognising that NCRA may help address existing perverse incentives, such as the tendency to pursue management practices that favour high productivity during 'good' years but which can increase exposure to losses during 'bad' years, as Hughes, Lawson and Valle (2017) have found in relation to Australian broadacre cropping.

[38] http://www.abs.gov.au/ausstats/abs@.nsf/0/58529ACD49B5ECE0CA2577A000154456?Opendocument (accessed 18 November 2019).

This is important to consider in the context of global climate change and the likely increased occurrence of extreme weather events (IPCC, 2013).

A vast amount of relevant natural capital-related data is already available in Australia, particularly with respect to water, climate and soil related risks. More data and tools to access or analyse the data are continually being developed. Increasingly, environmental data is being made available in more user-friendly formats, e.g. via searchable online maps, as opposed to requiring Geographical Information System (GIS) skills, which has been identified as a barrier to financial sector use of such information in the past (Cojoianu et al., 2015). There is a trend towards integration of modelled data with measured data, which generally increases coverage and resolution, although – as with measured data – it remains important to understand the uncertainty in the modelled data. As producers move towards increasing digitisation of their own management data, and integration of data feeds from a wide variety of both in-field and remote sensing technologies (Bronson and Knezevic, 2016; Keogh and Henry, 2016; Wolfert et al., 2017), there is increasing scope for producer data to be shared with other parties, such as lenders, on a suitably confidential and consensual basis, and for this to be integrated with national or regional level environmental data. However, in order for this to be achieved, much further work is required in areas such as standardisation of natural capital indicators and measurement protocols, development of data interoperability standards and platforms, and verification or other means of assurance to ensure trust and overcome the moral hazard inherent in data exchange (ClimateWorks Australia, 2019). Generally, transaction costs of undertaking NCRA must be substantially reduced if it is to become mainstream practice.

Overall, we conclude that, for Australian sheep production, a relatively short list of 11 material natural capital dependency risks can be identified, and for all of these, at least moderately practicable indicators and data sources to assess these risks are available. It is therefore plausible that a credit decision based on consideration of these indicators would better predict the risk of adverse outcomes, compared with current practice. In order to test this hypothesis, further research is required to investigate the links between the identified indicators, or similar alternatives, and long-term financial performance. It is vital that such research should take a long-term, dynamic and stochastic approach (Lien et al., 2007), as many natural capital risks have to do with conditions that change slowly over time (e.g. soil acidification or salinity), have dynamic effects (e.g. forced de-stocking due to drought may increase profit in the year in which sales are realised, but reduce profits in subsequent years) or are to do with extremes and variability rather than average conditions (e.g. rainwater availability or heat/cold stress). Furthermore, while it would be useful to test the correlation of individual risk indicators with financial performance, it is equally important to investigate whether a more holistic evaluation of natural capital risks *in toto* would provide more valuable decision support (Nelson et al., 2007; Tancoigne et al., 2014). Research is also needed on the level of correlation between indicators, which may enable a focus on a smaller sub-set, and on the value of risk mitigation policies and actions.

Despite the critical importance of farm profitability on both producer and lender decision-making, very little research has investigated the links between natural capital risks and farm profitability (Nelson et al., 2007; Robertson et al., 2009). This is partly because of the challenges in identifying and agreeing on suitable harmonised indicators (TEEB, 2018; Williams et al., 2019), and partly due to methodological issues to do with linking biophysical and economic models (Robertson et al., 2009). A major barrier is also the lack of availability of (or access to) robust, consistent, long-term farm financial performance data (Hughes et al., 2017). We suspect it is also partly due to a lack of communication and collaboration between academic communities (e.g. biophysical scientists and economists) and between academics, producers and the financial sector. We hope that our paper, in taking a financial sector perspective on natural capital risk which is informed by both academic and practitioner views, will provide impetus for further collaboration in future.

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