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REVIEW

The economics of drought: A review of impacts and costs

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Abstract

Although a growing body of literature studies drought impacts, papers providing a comprehensive review of drought's social and economic impacts are scarce. This paper fills this gap by exploring the consequences of drought on societies based on research findings in Australia—a large country used to experiencing severe droughts. To do this, we propose a framework to categorise drought impacts in three dimensions: individuals/households (including health), productive sectors and system (including economic and ecosystem) impacts. The framework then guides a systematic literature review and discussion of studies looking at diverse drought impacts and their related costs. By analysing and discussing the findings from this literature, we emphasise different policy considerations, empirical challenges and research needs to support robust analysis and estimates of the true cost of droughts. We conclude by proposing an expanded framework to identify drought impacts and a discussion of the implications of the review for policy development.

KEYWORDS

climate change, drought, extreme events, impacts and costs, macroeconomic impacts

JEL CLASSIFICATION

I18, Q10, Q54

1 | INTRODUCTION

Climate change research shows increases in the intensity, duration and spatial extent of droughts associated with higher temperatures (including heatwaves), decreased precipitation and increased evapotranspiration across the globe (IPCC, 2022a). Future drought may very well be the climate change impact with the most significant effect on agricultural regions (Hendy et al., 2018), which can bring substantive impacts beyond farms to supply chains, communities and society. Many rural areas that rely on their agricultural sector are particularly vulnerable to drought (McMichael et al., 2006), while towns and cities often experience impacts such as increased food insecurity, reduced amenity, water supply restrictions and dust (Cooper et al., 2019; Tozer & Leys, 2013). To identify strategies and opportunities to prepare, mitigate and adapt to drought impacts, a comprehensive understanding of potential impacts and their relative costs needs to be collated, quantified and monitored. This paper contributes towards this policy-relevant understanding by categorising the multiple impacts that drought can produce and reviewing studies assessing drought impacts and costs in Australia, a water-scarce country with a large agricultural sector.

International literature often cites Australia as a success story in drought management (e.g. Aghakouchak et al., 2014; Berbel & Esteban, 2019). The praise of Australia as a 'good' example is driven by the strategy the country has followed in combining water technology (including desalinisation plants), water pricing and markets, and education programmes, which were noticeably implemented during the Millennium drought between 1997 and 2009 (Aghakouchak et al., 2014). This reputation is also resembled by the large volume of research exploring different drought consequences in the country. However, despite the diverse literature on the topic, few scholarly attempts exist that comprehensively explore the wide range of impacts and costs of drought. In this paper, we attempt to fill this gap by reviewing the different types of impacts and costs that droughts cause in Australia. We aim to provide a wide review, so the reader can better understand how drought can affect societies. The review is supported by analysing data from a systematic literature review guided by a framework that categorises drought impacts.

1.1 | What is drought?

Drought has no universally adopted definition. However, intuitively, it can be considered an extended period of well below-average rainfall or water availability. In most cases, drought has no clear start or end point and can last from months to many years.

Four 'types' of drought are commonly distinguished: meteorological, agricultural, hydrological and socio-economic. Meteorological drought is a measure of dryness, often defined when rainfall in a region is measured to be at the lower extreme of experienced variation for a period of time (Wilhite & Glantz, 1985). Agricultural drought can result from meteorological drought and happens when available moisture affects plant growth and development (ibid). Hydrological drought is a reduction in surface flow, storage or groundwater levels relative to the historical levels of the region (Van Loon et al., 2016). In addition to impacts on agricultural production, hydrological drought can affect nonagricultural natural systems and extractive users, including urban communities and industry. Finally, socio-economic drought is when societies experience impacts from meteorological, agricultural or hydrological drought (Wilhite & Glantz, 1985).

All regions, by definition, experience periods of meteorological drought, but their exposure and capacity to withstand water availability disruptions will ultimately define how societies are impacted by drought. The perception of drought held by individuals, especially farmers, can also vary across regions and over time. For example, farmers in wetter areas are more likely to declare themselves in drought than farmers in similar but drier regions, even when they face the same proportional reduction in water availability (Hughes et al., 2020).

The FAO states that 83% of all damage and loss caused by drought worldwide is recorded by agriculture, of which crops and livestock are the main activities affected (FAO, 2017). Other economic sectors prone to drought disruptions include manufacturing, mining and energy generation (mainly hydropower), where water is essential for industrial processes such as cooling. Societies have sought to reduce the impacts of drought through, for example, various efficiency measures (improved irrigation systems and better crop varieties) or modifying water supply with dam construction or desalinisation plants (Van Loon et al., 2016). These interventions may increase the capacity of a region to reduce or avoid the potential impacts of water availability disruptions, implying that drought as a term might not be even invoked by those who would otherwise be adversely impacted.

The lack of a single universal definition of drought and the purpose-specific definitions used in different studies adds complexity to estimating the cost of drought (Bachmair et al., 2016). In this review, we partially mitigate this problem by focussing on insights and approaches taken from Australia's well-characterised multiyear large-scale droughts of the last 50 years (BOM, 2022), but considering that some impacts accrue outside the periods and regions where drought has occurred.

1.2 | Impacts as a function of exposure: A framework to categorise impacts

In addition to the challenges in defining thresholds that determine what can be considered 'drought', it is also challenging to identify and measure the diverse range of adverse impacts that drought can bring.

The impacts that a natural hazard such as drought can generate are a function of a region's exposure and absorption capacity. Exposure is defined by the population, infrastructure and assets, production and wealth-generating systems, and ecosystem features that face the disruptions caused by shocks or hazards in a region (IPCC, 2022b). The United Nations Office for Disaster Risk Reduction adds that exposure also includes areas indirectly exposed to the changing behaviour or disruptions that are induced by the event (Noy et al., 2020). Considering the definition of exposure, a framework to categorise drought impacts can be depicted as in Figure 1. As seen, potential impacts can affect three dimensions in a region: people (individuals and households), productive sectors (affecting directly specific economic activities, in most cases agriculture) and those affecting ecosystems and the broader regional economy, including its infrastructure and macro-effects. The framework also points out that potential impacts in economic sectors can cross dimensions, affecting household welfare (e.g. reduced employment and income) and the overall regional economy (e.g. lower demand for inputs and services).

All regions are different, as is their capacity to withstand water access disruptions due to drought. However, to get a fuller picture of the potential impacts that drought can generate, the framework does not consider the absorptive capacity that can translate into some impacts not materialising in a region, sector or household. Instead, the framework allows categorising a broad range of multiple impacts across dimensions. We follow this framework to review the literature in Australia.

The remainder of the paper is structured as follows: Section 2 describes the research design, including the systematic literature review approach and outputs; Section 3 reviews and

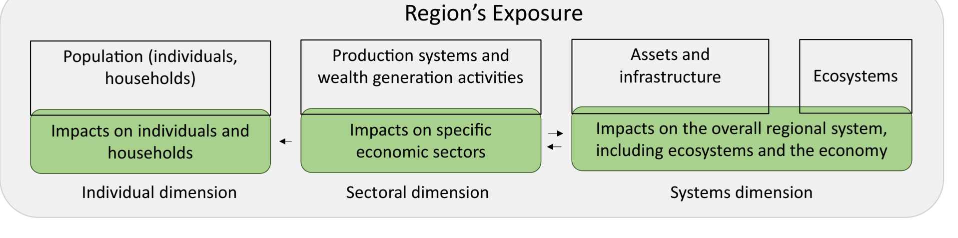

FIGURE 1 A framework to categorise drought impacts given exposure to drought in a region. Impacts on productive sectors can spill to individuals and whole systems. [Colour figure can be viewed at wileyonlinelibrary.com]

discusses the literature derived from the systematic approach, evaluating the impacts of drought across the different dimensions of Figure 1 and the macroeconomy; Section 4 discusses costs, empirical considerations to monetise impacts and policy interventions; and finally, Section 5 provides concluding remarks.

2 | METHODS

A systematic approach to capture research outputs examining aspects of drought impacts in Australia was employed. First, for scientific publications, a query analysis was conducted in Scopus—a repository that covers most scientific journals (Singh et al., 2021). The Scopus query focussed on the keywords impacts/costs/effects of drought in Australia. This query, conducted in April 2022, resulted in 1898 papers. Narrowing further the search to only papers with an economics subject, 52 papers were found and are listed in Table A2 in the Appendix S1—the Appendix S1 also includes more details of the systematic literature review process.

Data from the abstracts were used to estimate the number of papers looking at different drought impacts that fell within the three dimensions (Figure 1). Table 1 lists selected topics that summarise the findings discussed in more detail in the Appendix S1. Studies exploring the impact of health and well-being on individuals and households are numerous, but they are not frequently found in economic journals. Productive sector impacts, on the contrary, have received relatively high attention from economics and other disciplines. System-level impact evaluations show an interesting dichotomy; while economics papers dominate macroeconomic and labour studies, economics is limited in the ecosystem services literature.

In addition to the systematic literature review of scientific outputs, we also discuss some findings and implications reported in articles and reports in the grey literature. Although not exhaustive, we attempt to capture key studies analysing drought impacts and discuss some of their implications below—see the Appendix S1 for details on the selection of this literature for inclusion.

TABLE 1 Number of papers discussing drought impacts in Australia.

Impact dimension[a]	Number of studies in the broad literature ($n = 1{,}898$)	Number of studies in the economics literature ($n = 52$)
Individual		
Health (overall)	167	5
Mental health (stress)	287	2
Well-being/welfare	57	7
Water quality	69	0
Productive sectors (sectoral)		
Production	316	16
Productivity	70	10
Agriculture	122	29
Systems		
GDP/GRP	8	6
Labour	11	4
Ecosystem services	19	0

[a]Dimensions as defined in the framework of Figure 1. Values reflect the number of papers with the respective keyword(s) mentioned in their abstract—a fuller list and discussion are provided in the Appendix S1. The broad literature includes most science disciplines, while the economics literature includes only papers published with an 'economics' subject area.

Source: Authors, using data from Scopus.

3 | A REVIEW OF THE EVIDENCE OF DROUGHT IMPACTS

This section discusses findings from the literature on drought impacts, following the dimensions in the framework (Figure 1). We aim to identify impacts and, when possible, point to the identified economic value of the impact through their monetary cost. Many identified impacts have no direct market valuation, and, in most cases, researchers have not attempted to translate impacts into monetary terms. Empirical approaches that could be used to estimate the cost of an impact are discussed in Section 4.

3.1 | Individual dimension—Evidence of drought impacts on human health and well-being

Drought can bring a range of impacts on an individual's health and well-being. Research in Australia has focussed on two major impacts: mental and physical health effects. The latter includes consequences from increased heat, dust or smoke from bushfires and increased health risks from water access and sanitation issues. However, in an international context, impacts on the supply of food and even potable water are much more important—see Stanke et al. (2013) for a review of international evidence.

3.1.1 | Mental health impacts

Adverse mental health problems can result from an ongoing drought affecting farmers and agricultural workers (Vins et al., 2015) and, by extension, agriculturally dependent communities (Ellis & Albrecht, 2017; Stain et al., 2011). Many studies have found a general link between drought and farmer stress or poor mental health (e.g. Carroll et al., 2009; Edwards et al., 2015; Hanigan et al., 2018). These studies conclude that drought-induced mental distress predominantly affects younger farmers (Austin et al., 2018), those with lower financial security or low incomes due to drought (Yazd et al., 2020), those who live and work in geographically remote locations (Austin et al., 2018) and carers (Hunter & Edwards, 2011). Wheeler et al. (2018) also find that an increased risk of recurring drought is associated with a high rate of psychological distress in horticulturists, followed by broadacre, dairy and livestock farmers. At the community level, Edwards et al. (2015) calculated that the overall incidence of mental health problems in rural areas would be 10.5% lower if the population were not exposed to drought. Hanigan et al. (2012) suggest that the effects of drought-induced mental distress on the broader community are explained by two links: financial stress in farmers and communities; and environmental degradation that can take a psychological toll—an effect known as 'Solastalgia' (Albrecht et al., 2007). Higher stress caused by drought can also indirectly increase risk factors such as substance abuse (Measham et al., 2016) and gender-based violence (Whittenbury, 2013).

Looking within rural communities, it has been found that older women cope better with drought distress. This has been hypothesised to be due to women having higher social support and capacity to learn to cope with adversity than men (Powers et al., 2015; Stehlik, 2003). Yet, drought can also cause structural shifts in farm labour under cost pressure, resulting in women, in particular, taking on more physical tasks and resulting stress (Alston, 2006).

Beyond mental distress, two studies focussing on NSW found a link between drought incidence and suicide rates in men (Nicholls et al., 2006; Hanigan et al., 2012). The latter applies statistical modelling to evaluate suicide cases against the Hutchinson Drought Index (a metric that integrates consecutive months of lower-than-median rainfall in a region (Smith et al., 1992)), finding that 9% of all deaths in four decades in men aged 30–49 in drought-affected communities were the consequence of suicide associated with drought. The study also finds that the link between suicide and drought is strong even in cohorts of younger men (aged 19–29 years). The authors suggest that future research should consider the causation of suicide using a holistic framework involving financial, physical, social, and human factors and natural influences, such as season and climate change. Contrary to the findings from NSW, although without applying statistical modelling, Guiney (2012) claims that there is no clear evidence of the link between drought and suicides in Victoria.

3.1.2 | Physical health

Drought is commonly associated with periods of extended and more extreme heatwave conditions in Australia (Nicholls & Larsen, 2011), which can have a range of health consequences (Peng et al., 2011). Drought can impact physical health directly via air and water quality deterioration. These impacts are likely to be more significant for those who live and work close to the source (i.e. farm labourers and rural communities), but they can also impact regions far from those directly experiencing drought, such as the case of dust pollution affecting large cities such as Sydney (Johnston et al., 2011).

3.1.3 | Impacts via water quality (and quantity)

Although direct health impacts of water quality are less common in developed economies, drought can affect domestic and industrial water supply systems, including reducing the effectiveness of filtering and increasing susceptibility to toxin bypass. In addition, declining conditions of water sources lead to a rise in the concentration of toxins from contaminants, algal blooms and pathogens (Mosley, 2015). Likewise, postdrought inflows bring other problems, as demonstrated by Sydney Water's experiences with increased organic contaminants (such as dissolved carbon) after the Millennium drought (Mohiuddin et al., 2020), or phosphorus influx (Ancev & Madhavan, 2022).

Australian examples of drought-related health impact via alteration of water quality include arsenic and acidity contaminants reported for Perth aquifers (Appleyard et al., 2006), and poor odour and taste of potable water that can lead to substitution with soft drinks and sugary cordials (Fryer, 2019). Drought has also been associated with pathogen outbreaks such as Cryptosporidium (Lal & Konings, 2018) and cyanobacterial algal blooms (Bond et al., 2008; Mosley, 2015). Cyanobacterial toxins, for example, can mean nonconventional water treatments are necessary before water can be drinkable, costing up to $240 million annually in Australia (Atech, 2000; Westrick, 2008).

3.1.4 | Impacts via air quality

Air quality impacts of drought have received relatively little attention in Australia, despite a history of drought-exacerbated dust storms and bushfires (Tozer & Leys, 2013). Drought generally increases farmer exposure to dust regularly and persistently, but dust and smoke can be transported over long distances, impacting different communities (Rumchev et al., 2019). This geographic spillover affects individuals in areas not affected by drought.

Direct and immediate impacts of dust and smoke cause increased hospitalisation for respiratory issues (see Hime et al., 2015, for a review of Australian and international evidence). Pathogens and contaminants can also spread through dust. For example, rates of Q fever infections increased under drought conditions (Archibald, 2019), and dust storms have been linked to a Listeria contamination event of melons in NSW (NSW DPI, 2018). Depending on the composition, dust also develops long-term health conditions such as silicosis (Middleton et al., 2019; Schenker, 2000; Stanke et al., 2013). While air quality impacts can be transitory for physical health, the constant 'sweeping up' of dust can also compound the broader mental health impacts on regional populations.[1]

3.1.5 | Other household-level impacts

Beyond the effect on business, farm households and other households in agricultural regions can face significant financial burdens from impacts felt by productive sectors. Edwards et al. (2019) claim that farm households in areas of drought are 1.4 times more likely to report financial stress than similar households in non–drought areas. This financial stress can include reduced expenditure on recreational activities, disrupted payment of school fees and increased need for off-farm employment (Aslin & Russell, 2008). In addition, due to severe drought, Sherval and Askew (2012) state that families have had to adjust or abandon succession plans, especially where multiple generations live on one farm.

3.2 | Productive sectors dimension

Drought disrupts sectors of the economy that need water as an operational input. Given the context of Australia, we focus on impacts in the agricultural sector. However, other sectors, such as electricity generation, mining and manufacturing, are also affected by drought. For instance, Plumb and Davis (2010) claim that drought has contributed to an increase of as much as $10 extra per megawatt hour in wholesale electricity prices in Australia due to reduced supply from hydroelectric and coal-fired electricity generation plants—this last as a consequence of a lack of water for cooling processes.

The most visible impacts of drought on the agricultural sector are observed through failed crops, denuded landscapes and famished livestock. Australian research has mainly focussed on two scales of impact on productive sectors: (i) individual farm or enterprise scale, usually as average farm impacts, occasionally differentiated by region or commodity; and (ii) whole of the agricultural sector (albeit still sometimes geographically limited), occasionally inclusive of upstream and downstream supply chain elements.

3.2.1 | Economic impacts at the farm/enterprise scale

The economic impacts of drought create winners and losers in agriculture (O'Meagher, 2005). Winners include farmers able to benefit from higher prices locally (e.g. those who have fodder or water to sell), while losers are those unable to produce due to drought or those who have to pay higher prices for water or other inputs. When droughts become longer term or more severe, distributional impacts (the difference between losers and winners) can be accentuated and extended to entire regions.

Evaluating drought's impact on agriculture is complex because droughts can affect agricultural productivity, outputs and input prices through diverse processes. For example, a severe drought may change farmers' choice of input mix in production or the efficiency of machinery/intermediate input use, which could also be affected by technological progress. There can also be additional on-farm costs from drought disruptions, such as additional pumping and maintenance or switching from surface to groundwater. Similarly,

[1]We thank a reviewer for this important point.

operational costs associated with changes to labour requirements or fodder transport will impact farms differently. Table 2 lists studies that estimate drought impacts on agriculture in Australia at the farm scale.

Enterprise-scale studies have shown that livestock income may not be as seriously affected during the drought period itself; however, impacts can be felt later, during the drought recovery period, when restocking and herd rebuilding expenses are incurred. On this, Hooper et al. (2008) show that beef farm cash receipts decreased around 11% in the 2006–2007 drought period due to reduced calf production and lower cattle prices caused by increased drought-related turn-off and producers selling more unfinished or younger animals. During recovery (in 2007–2008), farm cash receipts of 'cattle enterprises' were likely to fall by a higher rate, −17%, due to fewer sales as farmers prioritised rebuilding their herds. For cropping enterprises, the outputs in the immediate years after a drought can also be misleading (such as the 31% increase value shown by Hooper et al., 2008) because cropping can rebound quickly following a drought, not only because of higher rainfall but also driven by a range of other factors including a need for additional cash income, disruption to crop–livestock mixes and crop–pasture rotations. These temporal effects are relevant to economic assessments because immediate periods before or after a drought can show farm performance indicators abnormal to more 'typical' years.

Although restricted to broadacre farms, Hughes, Soh, et al. (2019) describe a microsimulation model (*farmpredict*) that considers intertemporal specifications to estimate annual climate variability (including drought) farm-level impacts in the long run. Applying it, Hughes, Galeano, and Hatfield-Dodds (2019) find that a one-in-10 dry year typically tips the income of an average cropping farm from a $230,000 profit to a $125,000 loss and for an average beef farm from a $60,000 profit to a $5000 loss. Beyond intertemporal aspects, inter-regional effects are also essential to monitor geographically extended droughts. Farm survey data can support assessments of regional variability.[2] An example is Martin and Topp (2020), who use survey data to note that for the 2019–2020 drought, farm income in NSW varied from an average income loss of approximately $90,000 across farms in the North-West Slopes and Plains to an average $21,000 loss across farms in the south-east region. ABARES (2008) also uses farm survey data to report that farm incomes in 2006–2007 were almost $30,000 less than in the previous year and that the number of farms with negative cash income doubled to 42%.

Droughts also have a range of strategic and structural effects on farmers as they adjust their enterprise to climatic, regulatory and financial pressures. For instance, farmers have made substantial investments to improve water efficiency in some areas (Adamson et al., 2017; Kirby et al., 2014), with some forced to establish structural change towards increased cropping—see Kingwell and Xayavong (2017) for a case study in Western Australia. During the Millenium drought, Edwards et al. (2009) report that farms substantially reduced their output and increased financial hardship, while Nicholson et al. (2011) claim that around 70% of agricultural landowners received financial support. In the extreme, drought and increased temperatures can cause farmers to exit agriculture altogether (Wheeler & Zuo, 2017).

3.2.2 | Whole sector impacts

The impacts of major droughts on agricultural enterprises extend beyond direct production losses. Sheng and Xu (2019) find that Australia's agricultural total factor productivity grew by

[2]For instance, https://www.agriculture.gov.au/abares/research-topics/surveys

TABLE 2 Farm-scale estimates of drought impacts inAustralia—select studies.

Study	Drought period	Impact measure	Drought impact[a]
Purtill (1983)	1982–1983	Proportion of farms impacted	60%
		Total crop production	−28%
		Total wheat production	−40%
		The net value of rural production	−46%
Campbell et al. (1983)	1982–1983	Volume of production	−18%
		Farm receipts	−23%
		Farm cash operating surplus	−50%
Martin (1995)	1982–1983	Real farm business profit	−$38,000
Martin (1995)	1992–1994	Broadacre farms impacted	38% (1 year) 12% (2 years)
		Average farm cash income	−52% (1 year) −83% (≥2 years)
		Pastoral zone stock numbers	−38% sheep −5% cattle
Martin et al. (2003)	2002–2003	Broadacre farm cash income	−56%
		Production of winter crops	−60%
		Dairy farm cash income	−80%
		Summer crop area	−40%
		Summer crop production	−60%
		Farm business profit	-$89,000
Lu and Hedley (2004)	1994–1995	Farm production	−20%
	2002–2003	Farm production	−25%
Hooper et al. (2008)	2006–2007	Broadacre farm cash income	−41%
		Farm business profit	-$42,000
		Wheat and other crop income	−28%
		Dairy farm cash income	−61%
		Beef farm cash receipts	−11%
Hooper et al. (2008)	2007–2008 (recovery period from the previous year)	Farm cash income (NSW)	−27%
		Grain farm incomes	+31%
		Beef farm cash receipts (herd rebuilding)	−17%
Martin and Topp (2018)	2018–2019	Farm cash income	-$70,000
		Farm business profit	-$21,000
Martin and Topp (2020)	2019–2020	Farm cash income (vs 2018–19)	−8%
		Farm cash income (vs 10-year average)	−4%
		Farm business profit (vs 2018–19)	-$21,400
		Farm business profit (vs 10-year average)	-$62,000
RBA (2020)	2017–2020	Decline in farm GDP over the period	−30%
Hughes, Galeano, and Hatfield-Dodds (2019)	1 in 10 dry (calendar) year	Broadacre cropping farm profit	-$355,000
		Beef farm profit	-$65,000

[a]Drought impacts are a variation from the immediate previous year unless otherwise stated. Dollar values are nominal.

1.8 per cent points per year less due to the Millennium drought.[3] Chambers et al. (2020) used nonparametric productivity measurements to analyse differences in agricultural productivity across regions before and after the advent of the Millennium drought, finding that a primary determinant of agricultural productivity slowdown was not a slowdown in technological innovation but climatic-related changes in the pattern and rate of diffusion of technological advances.

[3]The authors use a synthetic control using weighted data from New Zealand, Argentina, the USA, Canada, Israel and Denmark.

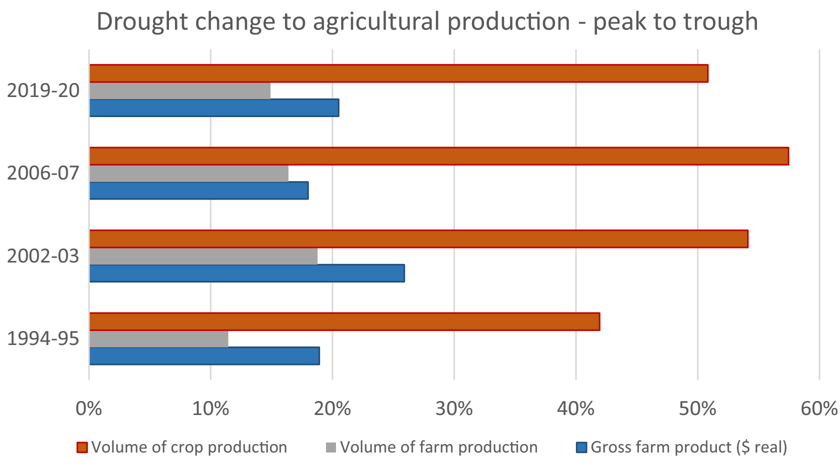

FIGURE 2 Approximation of drought-induced impacts on agricultural production for Australia—peak to trough (see text for caveats). Years show periods of widespread drought in Australia. Percentages show a drop (trough) from the previous highest value (peak) of the respective series: In all cases is the previous financial year, except for 2019–20, which shows declines from 2016–17. Volumes are given by ABARES' farm production indexes. Total farm production includes crops and livestock. *Source*: Authors, based on data from ABARES (2020). [Colour figure can be viewed at wileyonlinelibrary.com]

Using data from ABARES (2020), in Figure 2, we present an approximation of the physical production impacts of drought across the Australian farm sector for value and production volume. The figure plots the percentage drop of the respective variable in drought years compared with its previous highest point (a 'peak to trough' representation). Consistent with the farm-scale discussion, Figure 2 shows that cropping suffers the most volumetric impact—with production reductions between 40 and 60 per cent of previous highs. The overall volume of farm production (including livestock and crops) is much less impacted, falling by 11 to 19 per cent of the prior high. On the contrary, the financial implications of lower production impacts of drought will depend in part on prevailing prices. The difference in gross value of production (in real terms) shown in Figure 2 varies between 20% and 32% or up to a third of gross farm product relative to the best previous year. Although these are approximations of impact measures—the figure does not identify the marginal impact of drought across these changes that other factors beyond drought can influence—it is an intriguing correlation of declines with drought episodes in the country.

3.2.3 | Potential impacts on land values

Land values are associated with expectations about future returns and should not be impacted by drought directly in the short term unless there is widespread distress selling of farms. Evidence from several reports from the 'Rural Bank' seems to confirm the hypothesis by showing that land values in drought-affected areas have not been affected in the short term, although drought does tend to suppress the market activity resulting in fewer farmland transactions (e.g. Rural Bank, 2020). Long-term drought can have more detrimental effects on expected future returns, affecting land values negatively; however, the Australian evidence available so far seems not to support this hypothesis (Productivity Commission, 2009).

Empirically, the effect of drought on farmland values can be captured with hedonic models. To our knowledge, the study by Chancellor et al. (2019) has been the only attempt to measure what factors drive farmland values in Australia using hedonic modelling. Although no discussion on drought impacts is provided, the authors found that rainfall positively and significantly affects land values across Australia (elasticity ~5%), with a higher influence in the Wheat Sheep Zone (~20%).

3.3 | System impacts: Ecosystems and the broader economy

3.3.1 | Effects on ecosystem services and habitats

Drought impacts extend beyond water scarcity for agricultural production into various impacts on ecosystem services. Studies looking at impacts on ecosystem services in Australia include the following: provisioning riparian and wetland habitat; regulating services relating to channel navigation and bank stability, river mouth and associated dredging, acid sulphate soils in lake substrates and elevated river water salinity (and the consequent impact on production and infrastructure), vegetation moisture content and flammability, protection of soil health (including reducing wind and water erosion and stored carbon losses); and supporting habitat for vulnerable vegetation and associated fauna (Banerjee et al., 2013; Bond et al., 2008; Mosley, 2015; Pham et al., 2010). Drought can also induce high water temperatures, which, combined with low oxygen, can negatively impact fish populations (Australian Academy of Science, 2019).

Banerjee et al. (2013) identify threshold impacts, whereby some lost ecosystem services cannot be effectively replaced, such as riverbank slumping due to low water levels, loss of mature trees and potential loss of fish species. Similarly, environmental water releases have been required during drought to support riverine health (Bond et al., 2008). Still, they are often suspended due to the opportunity costs to agriculture or urban users (Grant et al., 2013). Drought can also lead to desiccated vegetation and, consequently, higher rates of wildfires (Gibbs, 1984).

Loss of vegetative cover from drought can leave soil surfaces exposed to consequent wind and water erosion risk, augmenting the incidence of dust storm events. For example, a single major dust storm, the 'Red Dawn' event in 2009, was estimated to result in the loss of 2.54 million tonnes of soil, including soil carbon, equating to nearly 1 million tonnes of CO_2 equivalent. The significant economic impacts of the storm were not on agriculture but instead on cleaning and other implications in urban communities far distant from the source of the dust, with total costs amounting to almost $300 m (Tozer & Leys, 2013). Denuded soils also often have reduced biological function, leading to drifting and moisture repellence in sandy systems and crusting in others, consequently reducing infiltration, plant recruitment and growth.

To our knowledge, Banerjee et al.'s (2013) study is the only Australian study that quantitatively analyses the economic costs of drought on various ecosystem services. The authors estimate that more than $810 million in costs were incurred for three years to mitigate losses, replace ecosystem services and adapt to new ecosystem equilibria in the South Australia portion of the Murray River during the Millennium drought.

3.3.2 | Broader impacts on communities and regional economies

The broader impacts on communities and regional economies depend on the level of exposure to drought. A larger economy is less likely to be dependent on agricultural production, so less affected by drought impacts in relative terms. For example, small rural towns with populations below 1000 are usually more dependent on agriculture, with their fortunes fluctuating more closely with drought, while the proportion of income derived from agriculture falls off rapidly as town size increases (Levantis, 2001). Exposure can be assessed by the significance of agricultural employment. Direct exposure would be given by the number (and share) of people employed in the agricultural sector, while an assessment of job multipliers can measure indirect exposure to determine the effect of agriculture on the broader regional economy. The higher the job multiplier of agriculture, the higher the indirect exposure of the region to drought. Although evidence is limited to a couple of case studies, research shows that this indirect effect has even negatively affected school enrolments in regions facing drought in Australia (Alston & Kent, 2006). Disruptions can also lead to decreases in social capital among drought-stricken communities, especially trust and reciprocity, which can affect the long-term functionality of regions (Fleming et al., 2014; Sherval & Askew, 2012). This can be exacerbated by depreciation in infrastructures and facilities due to drought conditions and decreased revenue for maintenance.

Some studies have focussed more directly on the impact of drought on urban amenities, including the private costs of water restrictions on household utility across gardening and household use and the public costs of urban green space. For example, Brennan et al. (2007) find that the private cost of water restrictions, depending on severity, is between $100 and $870 during summer months, while Cooper et al. (2011) estimate this cost as $40–$150 per year per household. Hensher et al. (2006) estimate households are willing to pay up to $240 per year to avoid a complete sprinkler ban. Poor water quality due to drought can adversely impact water quantity for community use, such as urban water supply, recreational opportunities, local food production and processing, and other industrial activities. In the Australian context, drought events and population growth have resulted in the federal and state/territory governments heavily investing in reverse osmosis plants and infrastructure to sustain urban water supply across cities and towns (Khan et al., 2015; Low et al., 2015). However, most desalination plants built to address water shortages during the Millennium drought have rarely operated. Appraising these initiatives, the Productivity Commission (2011) concluded that investment in desalination might have been too soon, too large and thus more expensive than other options.

Cultural and amenity services can also be affected due to the closure of camp and mooring sites, relocation of boats and loss of tourism due to unavailable recreation opportunities or distressing and unattractive environments as a consequence of drought (Rolfe & Dyack, 2011).

3.4 | Macroeconomic impacts

Water disruptions during drought events can affect regional and national economies through direct and less direct aggregated impacts on supply chains and economic feedbacks. Drought disruptions at the national scale and other large shocks to the system are commonly explored through their impact on national gross domestic product (GDP) and employment. For example, Horridge et al. (2005) estimated the direct production effects of the 2002–2003 drought to be around one per cent of Australia's GDP, and indirect impact a further 0.6%. Wittwer and Griffith (2011) take the approach further by decomposing the impacts of drought for the southern MDB using a computable general equilibrium (CGE) method to identify the effects on different large regions. Their study shows GDP for the southern MDB falling by 5.7% for the 2006–2007 to 2008–2009 drought. In a similar approach, for the 2017–2019 drought in NSW, Wittwer and Waschik (2021) show that the state's GDP was 0.7% lower in 2017–2018 and 1.3% lower in 2018–2019 and 2019–2020 (approx. $2.6 billion and $5.5 billion, respectively), compared with no-drought scenario estimates, with GDP dropping as much as 15% in New England and North West NSW. A range of macroeconomic estimates from different studies are summarised in Table 3.

TABLE 3 Macroeconomic estimates of drought impacts in Australia—select studies.

Study	Drought period	Impact estimate
Campbell et al. (1983)	1982–1983	−1.1% GDP −2% employment
Horridge et al. (2005)	2002–2003	−1.6% GDP
Lu and Hedley (2004)	2002–2003	−0.9% GDP −0.75% employment
ABS (2006)	2006–2007	−0.5% GDP
Wittwer and Griffith (2011)	2006–2007 to 2008–2009	−5.7% SMDB GDP (−1.3%) SMDB employment
Wittwer and Waschik (2021)	2018–2019 and 2019–2020	−1% NSW GDP in each year
RBA (2020)—February economic statement	2017–2020	−30% in farm GDP −18% in rural exports

Notes: Economic impacts are shown for the whole country unless otherwise specified. Impacts are estimates relative to a modelled no-drought case in the same year. SMDB—Southern Murray–Darling Basin.

In addition to GDP effects, macroeconomic effects also include aggregated impacts of drought on national (or state) labour markets. As seen in Table 3, according to estimates, the drought of 1982–1983 cost approximately 200,000 jobs, the 2006–2007 drought affected some 6000 jobs across the SMDB, and the 2018–2020 drought was estimated to have impacted around 34,000 jobs in NSW.

In terms of long-lasting macroconsequences of drought, the Productivity Commission (2009, p. 61) states: '*The effect of drought on the GDP growth rate is essentially transitory because in the long-run, GDP growth depends on the growth rates of labour and capital accumulation and total factor productivity growth (that is, increases in output that occur for a given quantity of inputs), not temporary movements in the level of farm GDP*'. However, as noted earlier, Sheng and Xu (2019) argue that drought can indeed depress productivity improvements in the long run, reflecting that impacts can be more than transitory.

3.4.1 | Cost of government interventions

Although government expenditures to prevent, mitigate, manage and recover from drought impacts have been substantial in Australia (DAWE, 2020), we do not aim to discuss government interventions in-depth in this paper, as we intend to review drought impacts. Nevertheless, it is important to note a few aspects to illustrate the magnitude of public investments and the challenges associated with drought policy.

Providing examples of public interventions, O'Meagher (2005) summarises several public investments in Australia to mitigate drought impacts, which reached around $1.2 billion in 2002–2003. Nicholson et al. (2011) found that by the end of the 2002–2007 drought, the owners of around 70% of agricultural land in the country had received some level of drought-related government financial support. More recently, the 2021 interim report of the National Drought Agreement states that federal and state governments announced approximately $6.2, $0.95 and $8.5 billion for mitigation, community and regional support, and long-term resilience and preparedness (DAWE, 2020).

As a consequence of the Millennium drought (and population growth), different Australian governments incurred significant investments to sustain water supplies for human consumption (Khan et al., 2015; Low et al., 2015). For instance, the Queensland Government invested around $9 billion to link and augment supplies as part of the South East Queensland Water Grid (Spiller, 2008). Similarly, in Victoria, public investments have occurred in various water supply augmentation schemes, including the Wonthaggi Desalination Plant at $5.7 billion (Grant et al., 2013). This history of public urban water infrastructure projects built in the wave of the Millennium drought illustrates the complexities that can arise when climate alternates between periods of relative water scarcity (when the exigency to augment water supply holds sway) and periods of water abundance (when financial, environmental and equity concerns dominate).

Drought impact evaluations rarely include the costs incurred in policy implementation focussed on drought preparedness. However, the benefits of improved absorptive capacity can be understood as a-priori mitigation of the potential impacts that drought causes, reducing their related economic costs. Evaluations that include drought preparedness costs are not easy to conduct as they should consist of a wide range of public and private investments such as R&D in drought-resistant crop varieties, water storage infrastructure expenditure and on-farm financial, social and physical planning support. Although complex, such sunk costs (investments) will ideally be considered in drought cost evaluations.

4 | ASSESSING IMPACTS AS ECONOMIC COSTS

The paper so far references most drought consequences as impacts, given that in most cases they are not directly assessed as economic costs. However, any impact affecting human welfare and productive activities can be an economic cost to society. Hence, a key challenge for comprehensive benefit–cost analysis is translating impacts into financial terms. Ideally, monetary and nonmonetary aspects should be fully considered when assessing (and understanding) the costs that drought produces.

Some impacts are more straightforward to translate and evaluate in economic terms. For example, the direct loss of agricultural production and changes to input and commodity prices can be easily valued in monetary terms. However, even these more direct impacts are hard to evaluate given the complexities in attributing effects economically and the variability of (regions, communities and businesses) contexts. Other drought impacts are much more complex to analyse given their nonmonetary nature or indirect, delayed or nonmarginal impacts on local and national economies. These impacts often require complex methods, such as nonmarket valuation techniques or modelling approaches, to reduce them to economic terms. A set of studies have attempted to estimate the aggregated economy costs of drought for the country or state accounts (e.g. general equilibrium cost estimates as in Wittwer & Waschik, 2021), while others provide a more comprehensive analysis of costs but with a geographic or sectorial boundary (e.g. Kingwell & Xayavong, 2017, for grain farms in WA). However, none of the analyses to date has sought to incorporate the broader costs likely to occur across all dimensions nor to bring them together.

In many cases, data also need to be collected or collated in ways that would allow drought impacts to be disentangled from other contributing factors. In addition, the temporal implications of drought are also generally overlooked. Some impacts are likely to occur in the medium- and long term, so they need to be evaluated dynamically, considering the legacy effects of drought, such as out-migration and the reallocation of productive assets.

4.1 | Empirical considerations for cost evaluations

On health and well-being impacts, there is no integrated attempt in Australia to understand the chronic health impacts of drought on economic output or a comprehensive assessment across farming and broader communities. To address this gap, the expenditures of public health systems can be explored to identify economic impacts. For instance, knowing the cost of each additional hospital visit due to drought effects would be helpful.[4] In addition, the decline in mental or physical health would invariably affect labour productivity; therefore, the cost of productivity decline can also be used to assess part of the monetary consequences of drought arising from health outcomes. Such health/productivity effect analysis can also be aggregated at the regional level, as shown by Davlasheridze et al. (2018) for the United States. Another critical aspect is the quantification of the cost of additional deaths caused by drought. Although a very sensitive topic, during the COVID-19 pandemic different policy interventions to save lives were discussed in economic terms (Holden & Preston, 2020). Such approaches aiming to model the 'value of a statistical life' can also be used to evaluate the lethal consequences of suicides from distress triggered by drought (e.g. those estimated by Hanigan et al., 2012).[5]

On productive sector impacts, drought costs across enterprises can be complex to evaluate as multiple factors operate in the system, including temporal aspect encompassing preparedness, within event and legacy effects. As shown, many studies only estimate production or income 'drops' in years affected by drought versus the previous year. This means that costs can be underestimated, and the efficacy of investments in drought preparedness or within drought decisions with future consequences, such as destocking, cannot be adequately evaluated. To address this issue, enterprise-scale data at longer time frames are important to gather in the country consistently, so monitoring and evaluation of drought impacts can include temporal aspects. Time-series data of farms performance can be used in panel regression models to evaluate changes caused by drought disruptions in a robust way, while supporting and complementing microsimulation models, such as *farmpredcit*, to predict future impacts. Other approaches, such as the synthetic control evaluation used by Sheng and Xu (2019), can be adjusted to regional scales to evaluate structural/long-term effects on factors such as productivity and growth across farms and regions, taking into consideration proper indexes to measure productivity changes (O'Donnell, 2021).

On ecosystems and broader economic impacts, drought can induce regional population decline and disruption of social capital due to adverse effects. However, the ability to estimate the economic impacts of drought from social outcomes is challenging. Generally, research is based on small survey samples or is not easily comparable to people or areas unaffected by drought (Edwards et al., 2019). As such, it is hard to translate societal outcomes into monetary terms, but they could be assessed on a case-by-case basis considering the overall effects on production and productivity of not just farms but the overall regional economy. On the contrary, considering the abundant literature using contingent valuation in Australia (e.g. Bennett et al., 2004), a meta-analysis of such studies can significantly contribute to expanding our understanding of nonmonetary drought impacts across communities.

Finally, more can be done on macroeconomic aggregated impacts to identify and use within and between regional variability. While some studies provide drought economic impacts for the country or whole states, research has found significant differences when scrutinising results across regions. Spatially explicit models, such as spatial econometric specifications, can be developed and tested to explore better the nuance of drought impacts across regions. This can be particularly relevant for regions with agricultural sectors with diverse production (such as horticulture) and supply chain services.

[4]Using, for instance, data such as those available from the AIHW in Australia—https://www.aihw.gov.au/reports/hospitals/mh-costs-acute-patients-public-2012-13-to-2014-15/contents/summary.

[5]Correctly interpreted, the economic concept for the value of a statistical life, or the value of life years, is the value of increasing the survival probabilities marginally (Holden & Preston, 2020). The value of a life may be above or below the income lost from life. There is a wide range of estimates depending on the kind of choices that are used to infer the value of life. The Australian Government has used a value of $ 4.9 million as guidance for robust benefit–cost evaluations (Australian Government, 2019).

In general, if we were to apply the precautionary principle, it would be justifiable to assess costs associated with disasters, such as major droughts, using a comprehensive and holistic approach that includes costs across different dimensions and legacies. Such assessments could consider the upper bounds of scientifically derived cost estimates, so governments and society can evaluate whether it is worth or not funding mitigation and adaptation interventions. This paper moves this attempt a step forward with the collection of evidence presented and approaches to estimate costs discussed above.

5 | AN EXPANDED FRAMEWORK TO CATEGORISE DROUGHT IMPACTS

Based on the evidence discussed above and following previous drought impact frameworks (Ding et al., 2011; Freire-González et al., 2017), we expand the framework in Figure 1 by adding key examples of impacts identified above, differentiating short-medium-term to the long-term type of effects, as well as pointing to the potential of impacts to spill to other regions and the macroeconomic functioning of regions or countries. The expanded framework is shown in Figure 3.

As described in the first column of Figure 3, drought—directly and indirectly—impacts human health and well-being. As reviewed, direct effects relate to reduced amenity and recreation opportunities and benefits, adverse physical health impacts from poor air or water quality and increased temperature, and adverse mental health impacts from drought-driven stressors across finance, farm management and related factors. There are also indirect health and well-being impacts from drought via factors such as job loss or imposed reduction in hours of work, which can indirectly increase stress leading to risk factors such as substance abuse (Measham et al., 2016).

Moving into the next column of Figure 3, drought will cause direct adverse effects on economic sectors that significantly rely on water as productive input, agriculture being the primordial case in most regions. Reduced water availability can impact some farm businesses by decreasing production and increasing their input and operational costs. Drought can also

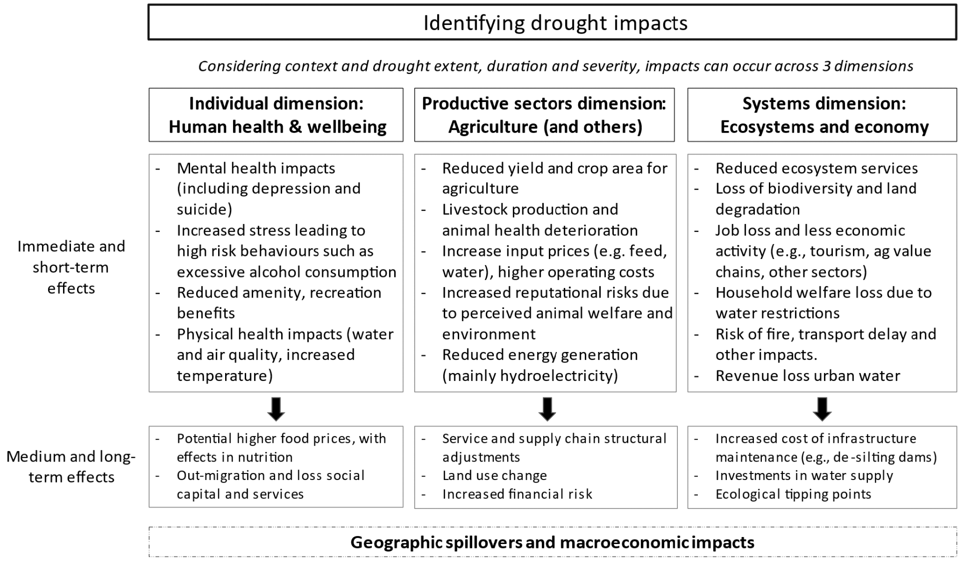

FIGURE 3 An expanded framework to identify and categorise drought impacts. *Source*: Authors.

adversely affect public perceptions of agricultural operations, such as erosion of public acceptance of irrigation production systems requiring large amounts of water in times of drought (an interesting example is almond and avocado farming in many regions—e.g. Sommaruga & Eldridge, 2020), or via animal welfare impacts in drought. Drought can also affect other sectors, such as energy systems (e.g. water shortage for hydroelectric power), mining and manufacturing.

The third column of Figure 3 details the relevance of broad and cumulative impacts on ecological and socio-economic systems (beyond a single sector). Reductions in ecosystem services reduce human welfare in affected areas and can eventually jeopardise the long-term survival of entire communities. Ecosystem service impacts include biodiversity loss and increased water and wind erosion. Included here are the indirect, cumulative effect of impacts on productive sectors through fewer jobs and less cash circulating in local economies—impacts on agricultural (or other sectors) productivity can eventually reduce labour demand and salary levels across regions.[6] Drought can also induce substantial public and private regional investments to ensure water supplies for human consumption and irrigation—which may not be the most efficient long-term option (Productivity Commission, 2021).

The bottom dashed box highlights the geographic spillovers and transmission of regional (or larger scale) impacts into the broader macroeconomy. Like other disruptive environmental events such as fires and floods, drought can cause effects beyond the regions directly affected. Thus, impacts across the three dimensions described in Figure 1 can also be felt beyond regions in drought. In other words, it can be the case that a region presents no sign of (meteorological or hydrological) drought but is still impacted as a consequence of drought elsewhere. Examples reported in Australia include impacts on air quality in cities due to dust generated by drought in a regional area. The larger the drought extent, duration or severity, the more likely geographic spillovers will occur. Macroeconomic impacts are likely to be more prominent in the case of severe long-term drought, extending across sectors and potentially inducing capital reallocation, productivity decline and population migration effects with consequences to the whole economy. Drought can also increase the aggregated demand for public health (e.g. mental health services), lower state revenues from taxes, cause increase demand for national unemployment benefits or other assistance and adversely affect supply chain industries of impacted sectors, such as agricultural exports.

Finally, it is essential to note the temporal considerations of the impacts depicted in the left-hand side portion of Figure 3. While primarily pointing to the specific effects likely to occur in the immediate/short term, other impacts are likely to materialise in the medium or long term through delayed impacts in ecological systems such as water supply systems (involving significant investments as those made in desalination plants), increased costs of infrastructure maintenance, longer term adjustments in the economy, including land use changes, or out-migration and the loss of local services.

6 | CONCLUSIONS

There is a large number of scholarly works looking at the impacts of drought in Australia. However, few studies exist that comprehensively explore the impacts and economic costs generated by drought across multiple dimensions. Available studies mostly explore the impacts on agriculture, sometimes including upstream and downstream impacts in the value chain or focussing on specific impacts in isolation, such as elements of health, dust storm events or

[6]Effects can of course go into the positive effect for some towns/sectors. For example, some landscaping and garden supply businesses may be adversely impacted by drought, while others such as covered outdoor recreational spaces could benefit generating employment and secured wages. We thank a reviewer for this observation.

urban water restrictions. Computable general equilibrium studies complement this literature, but they primarily identify a tail of impacts on aggregated regional outputs. Elements such as the diverse consequences of drought for the broader economy, specific consideration of mental health issues and deterioration of ecosystem services or the interaction of drought with social, economic and ecological stress are largely missing from the economic explorations to date. Further economic disruptions on vulnerable communities, such as some First Nations communities, are also barely explored (Rigby et al., 2011).

Our review implies that policy needs to consider broadening from the focus on agricultural impacts to a more comprehensive consideration of the costs of drought. For example, even though the FAO claims that globally 83% of all costs of drought are via agricultural production losses, our review indicates that this is most likely an overestimate, especially in the context of developed nations such as Australia, where agriculture constitutes a small part of the total economy. Yet, drought continues to impact large parts of the population, sometimes unexpectedly. For example, the expenses involved in potable water infrastructure for drought, health consequences on rural communities and ecosystem service impacts take a significant toll. Furthermore, the millions of dollars of public expenditure on drought assistance impose substantial opportunity costs on the national economy, although we acknowledge that current policy designs are more inclined to fund drought preparedness programmes and resilience investments.[7]

Finally, it is noteworthy to emphasise that drought impacts depend on context. Two regions with similar water stress can be affected differently depending on their exposure and coping ability. To prepare for drought, policymakers must evaluate a region's exposure and assess how natural and human-made conditions can reduce or even avoid some impacts altogether. However, as conditions vary, potential impacts can range widely across individuals, households, sectors, regional economies and ecosystems. Understanding all potential impacts is crucial for planning, especially with increased risks of drought frequency and severity due to climate change. This paper contributes a step further in this understanding by providing a framework to support a more explicit identification and categorisation of potential impacts and by discussing evidence and policy (and future research) implications of a wide range of impacts and costs generated by drought.

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REFERENCES

ABARES (Australian Bureau of Agricultural and Resource Economics). (2008) *Australian farm survey results 2005–06 to 2006–07*. Canberra, ACT: ABARES.

ABARES (Australian Bureau of Agricultural and Resource Economics). (2020) *Agricultural commodity statistics 2020*. Canberra, ACT: ABARES. Available from: https://doi.org/10.25814/RVVJ-PY73

ABS (Australian Bureau of Statistics). (2006) Catalog 5206.0 – Australian National Accounts: National Income, Expenditure and Product, Sep 2006. Feature article: Impact of the drought on agricultural production in 2006–07.

[7]As reflected by the 'Drought and Climate Adaptation Program' of the Queensland government or the 'Future Drought Fund' of the Federal government.

Adamson, D., Loch, A. & Schwabe, K. (2017) Adaptation responses to increasing drought frequency. *Australian Journal of Agricultural and Resource Economics*, 61(3), 385–403.
Aghakouchak, A., Feldman, D., Stewardson, M., Saphores, J.D., Grant, S. & Sanders, B. (2014) Australia's drought: lessons for California. *Science*, 343, 1430–1431.
Albrecht, G., Sartore, G.M., Connor, L., Higginbotham, N., Freeman, S., Kelly, B. et al. (2007) Solastalgia: the distress caused by environmental change. *Australasian Psychiatry*, 15, S95–S98.
Alston, M. (2006) 'I'd like to just walk out of here': Australian women's experience of drought. *Sociologia Ruralis*, 46(2), 154–170.
Alston, M. & Kent, J. (2006) *The impact of drought on secondary education access in Australia's rural and remote areas*. Wagga Wagga: Centre for Rural Social Research. Charles Sturt University.
Ancev, T. & Madhavan, K. (2022) Size matters: optimal management of dynamic systems with varying size. *Australian Journal of Agricultural and Resource Economics*, 67(1), 137–153.
Appleyard, S., Angeloni, J. & Watkins, R. (2006) Arsenic-rich groundwater in an urban area experiencing drought and increasing population density, Perth. *Australia. Applied Geochemistry*, 21(1), 83–97.
Archibald, J. (2019) Disease in the dust: experiences of Q fever during drought in Australia. *Perspectives in Public Health*, 139(2), 77–78.
Aslin, H. & Russell, J. (2008) *Social impacts of drought: review of literature*. Canberra, ACT: Bureau of Rural Sciences.
Atech. (2000) *Cost of algal blooms*. Canberra, ACT: Report to Land and Water Resources Research and Development Corporation.
Austin, E., Handley, T., Kiem, A. et al. (2018) Drought-related stress among farmers: findings from the Australian rural mental health study. *Medical Journal of Australia*, 209(4), 159–165. Available from: https://doi.org/10.5694/mja17.01200
Australian Academy of Science. (2019) *Investigation of the causes of mass fish kills in the Menindee region NSW over the summer of 2018–2019*. ACT: Canberra.
Australian Government. (2019) *Best practice regulation guidance note value of statistical life*. Canberra, ACT: Department of the Prime Minister and Cabinet, Office of Best Practice Regulation, Australian Federal Government. Available from: https://www.pmc.gov.au/sites/default/files/publications/value-of-statistical-life-guidance-note_0_0.pdf
Bachmair, S., Stahl, K., Collins, K., Hannaford, J., Acreman, M., Svoboda, M. et al. (2016) Drought indicators revisited: the need for a wider consideration of environment and society. *WIREs Water*, 3(4), 516–536.
Banerjee, O., Bark, R., Connor, J. & Crossman, N. (2013) An ecosystem services approach to estimating economic losses associated with drought. *Ecological Economics*, 91, 19–27.
Bennett, J., Van Bueren, M. & Whitten, S. (2004) Estimating society's willingness to pay to maintain viable rural communities. *Australian Journal of Agricultural and Resource Economics*, 48(3), 487–512.
Berbel, J. & Esteban, E. (2019) Droughts as a catalyst for water policy change. Analysis of Spain, Australia (MDB), and California. *Global Environmental Change*, 58, 101969.
BOM (Bureau of Meteorology). (2022) *Previous droughts*. Available from: http://www.bom.gov.au/climate/drought/knowledge-centre/previous-droughts.shtml
Bond, N.R., Lake, P.S. & Arthington, A.H. (2008) The impacts of drought on freshwater ecosystems: an Australian perspective. *Hydrobiologia*, 600(1), 3–16.
Brennan, D., Tapsuwan, S. & Ingram, G. (2007) The welfare costs of urban outdoor water restrictions. *Australian Journal of Agricultural and Resource Economics*, 51(3), 243–261.
Campbell, R., Crowley, P. & Demura, P. (1983) Impact of drought on national income and employment. *Quarterly Review of the Rural Economy*, 5(3), 254–263.
Carroll, N., Frijters, P. & Shields, M. (2009) Quantifying the costs of drought: new evidence from life satisfaction data. *Journal of Population Economics*, 22(2), 445–461.
Chambers, R.G., Pieralli, S. & Sheng, Y. (2020) The millennium droughts and Australian agricultural productivity performance: a nonparametric analysis. *American Journal of Agricultural Economics*, 102(5), 1383–1403.
Chancellor, W., Zhao, S., Randall, L., Lawson, K. & Hoang, K. (2019) *Measuring Australian broadacre farmland value*. Research by the Australian Bureau of Agricultural and Resource Economics and sciences [ABARES]. Technical report 19.7. Canberra, Australia: Department of Agriculture.
Cooper, B., Burton, M. & Crase, L. (2011) Urban water restrictions: attitudes and avoidance. *Water Resources Research*, 47(12), W12527.
Cooper, B., Burton, M. & Crase, L. (2019) Willingness to pay to avoid water restrictions in Australia under a changing climate. *Environmental and Resource Economics*, 72, 823–847.
Davlasheridze, M., Goetz, S. & Han, Y. (2018) The effect of mental health on US County economic growth. *Review of Regional Studies*, 48(2), 155–171.
DAWE (Department of Agriculture, Water and the Environment). (2020) *Interim National Drought Agreement Report*, Canberra, March. CC BY 4.0. Available at: https://www.agriculture.gov.au/ag-farm-food/drought/drought-policy/national-drought-agreement

Ding, Y., Hayes Michael, J. & Widhalm, M. (2011) Measuring economic impacts of drought: a review and discussion. *Disaster Prevention and Management: An International Journal*, 20(4), 434–446.
Edwards, B., Gray, M. & Hunter, B. (2009) A sunburnt country: the economic and financial impact of drought on rural and regional families in Australia in an era of climate change. *Australian Journal of Labour Economics*, 12, 109–131.
Edwards, B., Gray, M. & Hunter, B. (2015) The impact of drought on mental health in rural and regional Australia. *Social Indicators Research*, 121, 177–194.
Edwards, B., Gray, M. & Hunter, B. (2019) The social and economic impacts of drought. *Australian Journal of Social Issues*, 54(1), 22–31.
Ellis, N. & Albrecht, G. (2017) Climate change threats to family farmers' sense of place and mental wellbeing: a case study from the Western Australian wheatbelt. *Social Science & Medicine*, 175, 161–168.
FAO (Food and Agriculture Organisation of the United Nations). (2017) The impacts of disasters and crises on agriculture and food security. FAO report Available from: http://www.fao.org/3/I8656EN/i8656en.pdf
Fleming, D.A., Chong, A. & Bejarano, H.D. (2014) Trust and reciprocity in the aftermath of natural disasters. *The Journal of Development Studies*, 50(11), 1482–1493.
Freire-González, J., Decker, C. & Hall, J. (2017) The economic impacts of droughts: a framework for analysis. *Ecological Economics*, 132, 196–204.
Fryer, B. (2019) Families resorting to sugar drinks in drought-affected areas risk long-term health. NITV News article. Available from: https://www.sbs.com.au/nitv/article/families-resorting-to-sugar-drinks-in-drought-affected-areas-risk-long-term-health/yexgznjuo
Gibbs, W. (1984) The great Australian drought: 1982–1983. *Disasters*, 8(2), 89–104.
Grant, S., Fletcher, T., Feldman, D., Saphores, J.D., Cook, P.L., Stewardson, M. et al. (2013) Adapting urban water systems to a changing climate: lessons from the millennium drought in Southeast Australia. *Environmental Science & Technology*, 47(19), 10727–10734.
Guiney, R. (2012) Farming suicides during the Victorian drought: 2001-2007. *The Australian Journal of Rural Health*, 20(1), 11–15.
Hanigan, I., Butler, C., Kokic, P. & Hutchinson, M. (2012) Suicide and drought in New South Wales, Australia, 1970-2007. *Proceedings of the National Academy of Sciences of the United States of America*, 109(35), 13950–13955.
Hanigan, I., Schirmer, J. & Niyonsenga, T. (2018) Drought and distress in southeastern Australia. *EcoHealth*, 15(3), 642–655.
Hendy, J., Kerr, S., Halliday, A., Owen, S., Ausseil, A.-G., Burton, R. et al. (2018) *Drought and climate change adaptation: impacts and projections*. Motu Note #31. Wellington, NZ: Motu Economic and Public Policy Research.
Hensher, D., Shore, N. & Train, K. (2006) Water supply security and willingness to pay to avoid drought restrictions. *Economic Record*, 82(256), 56–66.
Hime, N., Cowie, C. & Marks, G. (2015) *Review of the health impacts of emission sources, types and levels of particulate matter air pollution in ambient air in NSW*. Centre for air Quality and Health Research and evaluation (CAR) and Woolcock Institute of Medical Research.
Holden, R. & Preston, B. (2020) The costs of the shutdown are overestimated –they're outweighted by its $1 trillion benefit. *The Conversation*. Available from: https://theconversation.com/the-costs-of-the-shutdown-are-overestimated-theyre-outweighed-by-its-1-trillion-benefit-138303
Hooper, S., Ashton, D., Crooks, S., Mackinnon, D., Nicols, P. & Phillips, P. (2008) Farm financial performance: Australian farm income and drought recovery, 2005-06, 2006-07 and 2007-08. *Australian Commodities: Forecasts and Issues*, 15(1), 243–264.
Horridge, M., Madden, J. & Wittwer, G. (2005) The impact of the 2002–2003 drought on Australia. *Journal of Policy Modeling*, 27(3), 285–308.
Hughes, N., Galeano, D. & Hatfield-Dodds, S. (2019) Analysis of the effects of drought and climate variability on Australian farms. *ABARES Insights*, 6, 1–10.
Hughes, N., Soh, W., Boult, C. & Lawson, K. (2020) *Defining drought from the perspective of Australian farmers*. Canberra, ACT: ABARES, Working paper.
Hughes, N., Soh, W., Lawson, K., Boult, C., Donoghoe, M., Valle, H. et al. (2019) *Farmpredict: a microsimulation model of Australian farms*. Canberra, ACT: ABARES, Working paper.
Hunter, B. & Edwards, B. (2011) The impact of drought on carers. *Australian Journal of Labour Economics*, 14, 199–214.
IPCC. (2022a) Summary for policymakers. In: Möller, V. et al. (Eds.) *Climate change 2022: impacts, adaptation, and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge: Cambridge University Press.
IPCC. (2022b) Annex II: glossary. In: Möller, V.V. et al. (Eds.) *Climate change 2022: impacts, adaptation, and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge: Cambridge University Press.

Johnston, F., Hanigan, I., Henderson, S., Morgan, G. & Bowman, D. (2011) Extreme air pollution events from bushfires and dust storms and their association with mortality in Sydney, Australia 1994–2007. *Environmental Research*, 111(6), 811–816.

Khan, S.J., Deere, D., Leusch, F.D.L., Humpage, A., Jenkins, M. & Cunliffe, D. (2015) Extreme weather events: should drinking water quality management systems adapt to changing risk profiles? *Water Research*, 85, 124–136.

Kingwell, R.S. & Xayavong, V. (2017) How drought affects the financial characteristics of Australian farm businesses. *Australian Journal of Agricultural and Resource Economics*, 61(3), 344–366.

Kirby, M., Bark, R., Connor, J., Qureshi, M.E. & Keyworth, S. (2014) Sustainable irrigation: how did irrigated agriculture in Australia's Murray–Darling basin adapt in the millennium drought? *Agricultural Water Management*, 145, 154–162.

Lal, A. & Konings, P. (2018) Beyond reasonable drought: hotspots reveal a link between the 'big dry' and cryptosporidiosis in Australia's Murray Darling basin. *Journal of Water and Health*, 16(6), 1033–1037.

Levantis, C. (2001) *Country towns: impact of farmers' expenditure on employment and population*. Australian Farm Surveys Report: Financial Performance of Australian Farms, 29–35.

Low, K.G., Grant, S.B., Hamilton, A.J., Gan, K., Saphores, J.-D., Arora, M. et al. (2015) Fighting drought with innovation: Melbourne's response to the millennium drought in Southeast Australia. *WIREs Water*, 2(4), 315–328.

Lu, L. & Hedley, D. (2004) The impact of the 2002-03 drought on the economy and agricultural employment. *Economic Round-Up*, 3(Autumn), 25–43.

Martin, P. (1995) *Drought: impact on farm financial performance*. ABARE Farm Surveys Report. Canberra, ACT: Commonwealth of Australia, pp. 58–64.

Martin, P., Hooper, S., Blias, A., Hanna, N. & Ford, M. (2003) Farm financial performance: drought cuts farm incomes after an excellent year in 2001-02. *Australian Commodities*, 10(1), 120–133.

Martin, P. & Topp, V. (2018) *Drought impacts on broadacre and dairy farms in south-eastern Australia*, ABARES research report 18.16. Canberra, ACT: Australian Bureau of Agricultural and Resource Economics and Sciences.

Martin, P. & Topp, V. (2020) *Farm performance: broadacre and dairy farms, 2017–18 to 2019–20*, ABARES research report., Canberra, ACT. https://doi.org/10.25814/5e45cc516f01b

McMichael, A.J., Woodruff, R.E. & Hales, S. (2006) Climate change and human health: present and future risks. *Lancet*, 367, 859–869.

Measham, T.G., Fleming, D.A. & Schandl, H. (2016) A conceptual model of the socioeconomic impacts of unconventional fossil fuel extraction. *Global Environmental Change*, 36, 101–110.

Middleton, N., Tozer, P. & Tozer, B. (2019) Sand and dust storms: underrated natural hazards. *Disasters*, 43(2), 390–409.

Mohiuddin, A.S.M., Cox, P. & Blayney, B. (2020) The impact of the millennium drought on water filtration plants. *Water e-Journal*, 5(1), 1–10.

Mosley, L.M. (2015) Drought impacts on the water quality of freshwater systems; review and integration. *Earth-Science Reviews*, 140, 203–214.

Nicholls, N., Butler, C. & Hanigan, I. (2006) Inter-annual rainfall variations and suicide in New South Wales, Australia, 1964-2001. *International Journal of Biometeorology*, 50, 139–143.

Nicholls, N. & Larsen, S. (2011) Impact of drought on temperature extremes in Melbourne, Australia. *Australian Meteorological and Oceanographic Journal*, 61(2), 113–116.

Nicholson, M., Bruce, S., Walcott, J. & Gray, J. (2011) Elements of a national drought policy: the Australian context. In: Sivakumar, M.V.K., Motha, R.P., Wilhite, D.A. & Qu, J.J. (Eds.) *Towards a compendium on National Drought Policy: proceedings of an expert meeting on the preparation of a compendium on National Drought Policy*. Washington, DC: World Meteorological Organization.

Noy, I., Doan, N., Ferrarini, B. & Park, D. (2020) Measuring the economic risk of COVID-19. *Global Policy*, 11(4), 413–423.

NSW DPI (New South Wales Department of Primary Industries). (2018) Listeria Outbreak Investigation: Summary Report for the Melon Industry.

O'Donnell, C. (2021) Measuring and explaining changes in productivity. *Farm Policy Journal*, 3(Autumn), 26–40.

O'Meagher, B. (2005) Policy for agricultural drought in Australia: an economics perspective. In: Botterill, L.C. & Wilhite, D.A. (Eds.) *From disaster response to risk management: Australia's National Drought Policy*. Dordrecht: Springer, Netherlands, pp. 139–155.

Peng, B., Williams, S., Loughnan, M. et al. (2011) The effects of extreme heat on human mortality and morbidity in Australia: implications for public health. *Asia Pacific Journal of Public Health*, 23(2_suppl), 27S–36S.

Pham, T.D., Simmons, D.G. & Spurr, R. (2010) Climate change-induced economic impacts on tourism destinations: the case of Australia. *Journal of Sustainable Tourism*, 18(3), 449–473.

Plumb, M. & Davis, K. (2010) *Developments in utilities prices*. RBA Bulletin, December, 9–17.

Powers, J.R., Dobson, A.J., Berry, H.L., Graves, A.M., Hanigan, I.C. & Loxton, D. (2015) Lack of association between drought and mental health in a cohort of 45-61 year old rural Australian women. *Australian and New Zealand Journal of Public Health*, 39, 518–523.

Productivity Commission. (2009) *Government drought support*. Report No. 46, Final Inquiry Report.

Productivity Commission. (2011) *Australia's urban water sector*, report No. 55, Final Inquiry Report.

Productivity Commission. (2021) National Water Reform 2020, Draft Report. Canberra, ACT.

Purtill, A. (1983) A study of the drought – overview. *Quarterly Review of the Rural Economy*, 5(1), 3–11.

RBA (Reserve Bank of Australia). (2020) *Statement on monetary policy, February 2020*. Available from: https://www.rba.gov.au/publications/smp/2020/feb/pdf/statement-on-monetary-policy-2020-02.pdf: Reserve Bank of Australia.

Rigby, C.W., Rosen, A., Berry, H.L. & Hart, C.R. (2011) If the land's sick, we're sick: the impact of prolonged drought on the social and emotional wellbeing of aboriginal communities in rural New South Wales. *Australian Journal of Rural Health*, 19(5), 249–254.

Rolfe, J. & Dyack, B. (2011) Valuing recreation in the Coorong, Australia, with travel cost and contingent behaviour models. *Economic Record*, 87(277), 282–293.

Rumchev, K., Gilbey, S., Mead-Hunter, R., Selvey, L., Netto, K. & Mullins, B. (2019) Agricultural dust exposures and health and safety practices among Western Australian wheatbelt farmers during harvest. *International Journal of Environmental Research and Public Health*, 16(24), 5009.

Rural Bank. (2020) Australian farmland values 2020 | New South Wales. Rural Bank Report. Available from: https://www.ruralbank.com.au/siteassets/knowledgeandinsights/publications/farmlandvalues/newsouthwales/afv-nsw-2020.pdf

Schenker, M. (2000) Exposures and health effects from inorganic agricultural dusts. *Environmental Health Perspectives*, 108(Suppl 4), 661–664.

Sheng, Y. & Xu, X. (2019) The productivity impact of climate change: evidence from Australia's millennium drought. *Economic Modelling*, 76, 182–191.

Sherval, M. & Askew, L.E. (2012) Experiencing 'drought and more': local responses from rural Victoria, Australia. *Population and Environment*, 33, 347–364.

Singh, V.K., Singh, P., Karmakar, M., Leta, J. & Mayr, P. (2021) The journal coverage of web of science, Scopus and dimensions: a comparative analysis. *Scientometrics*, 126(6), 5113–5142.

Smith, D.I., Hutchinson, M.F. & McArthur, R.J. (1992) *Climatic and agricultural drought: payments and policy*. Canberra, ACT: Centre for Resource and Environmental Studies, Australian National University.

Sommaruga, R. & Eldridge, H.M. (2020) Avocado production: water footprint and socioeconomic implications. *EuroChoices*, 20(2), 48–53.

Spiller, D. (2008) Water for today, water for tomorrow: establishment and operation of the SEQ water grid. *Australian Economic Review*, 41(4), 420–427.

Stain, H.J., Kelly, B., Carr, V.J., Lewin, T.J., Fitzgerald, M. & Fragar, L. (2011) The psychological impact of chronic environmental adversity: responding to prolonged drought. *Social Science & Medicine*, 73(11), 1593–1599.

Stanke, C., Kerac, M., Prudhomme, C., Medlock, J. & Murray, V. (2013) Health effects of drought: a systematic review of the evidence. *PLoS Currents*, 5.

Stehlik, D. (2003) Australian drought as lived experience: social and community impacts. In: Fisher, M. & Botterill, L. (Eds.) *Beyond drought: people, policy and perspectives*. Clayton, Australia: CSIRO Publishing.

Tozer, P. & Leys, J. (2013) Dust storms – what do they really cost? *The Rangeland Journal*, 35(2), 131–142.

Van Loon, A.F., Gleeson, T., Clark, J., Van Dijk, A.I., Stahl, K., Hannaford, J. et al. (2016) Drought in the Anthropocene. *Nature Geoscience*, 9(2), 89–91.

Vins, H., Bell, J., Saha, S. & Hess, J.J. (2015) The mental health outcomes of drought: a systematic review and causal process diagram. *International Journal of Environmental Research and Public Health*, 12(10), 13251–13275.

Westrick, J.A. (2008) Cyanobacterial toxin removal in drinking water treatment processes and recreational waters. In: Hudnell, H.K. (Ed.) *Cyanobacterial harmful algal blooms: state of the science and research needs*. New York, NY: Springer New York, pp. 275–290.

Wheeler, S.A. & Zuo, A. (2017) The impact of drought and water scarcity on irrigator farm exit intentions in the Murray–Darling basin. *Australian Journal of Agricultural and Resource Economics*, 61(3), 404–421.

Wheeler, S.A., Zuo, A. & Loch, A. (2018) Water torture: unravelling the psychological distress of irrigators in Australia. *Journal of Rural Studies*, 62, 183–194.

Whittenbury, K. (2013) Climate change, Women's health, wellbeing and experiences of gender based violence in Australia. In: Alston, M. & Whittenbury, K. (Eds.) *Research, action and policy: addressing the gendered impacts of climate change*. Dordrecht: Springer.

Wilhite, D.A. & Glantz, M.H. (1985) Understanding: the drought phenomenon: the role of definitions. *Water International*, 10(3), 111–120.

Wittwer, G. & Griffith, M. (2011) Modelling drought and recovery in the southern Murray-Darling basin. *Australian Journal of Agricultural and Resource Economics*, 55(3), 342–359.
Wittwer, G. & Waschik, R. (2021) Estimating the economic impacts of the 2017–2019 drought and 2019–2020 bushfires on regional NSW and the rest of Australia. *Australian Journal of Agricultural and Resource Economics*, 65(4), 918–936.
Yazd, S.D., Wheeler, S.A. & Zuo, A. (2020) Understanding the impacts of water scarcity and socioeconomic demographics on farmer mental health in the Murray-Darling basin. *Ecological Economics*, 169, 106564.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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