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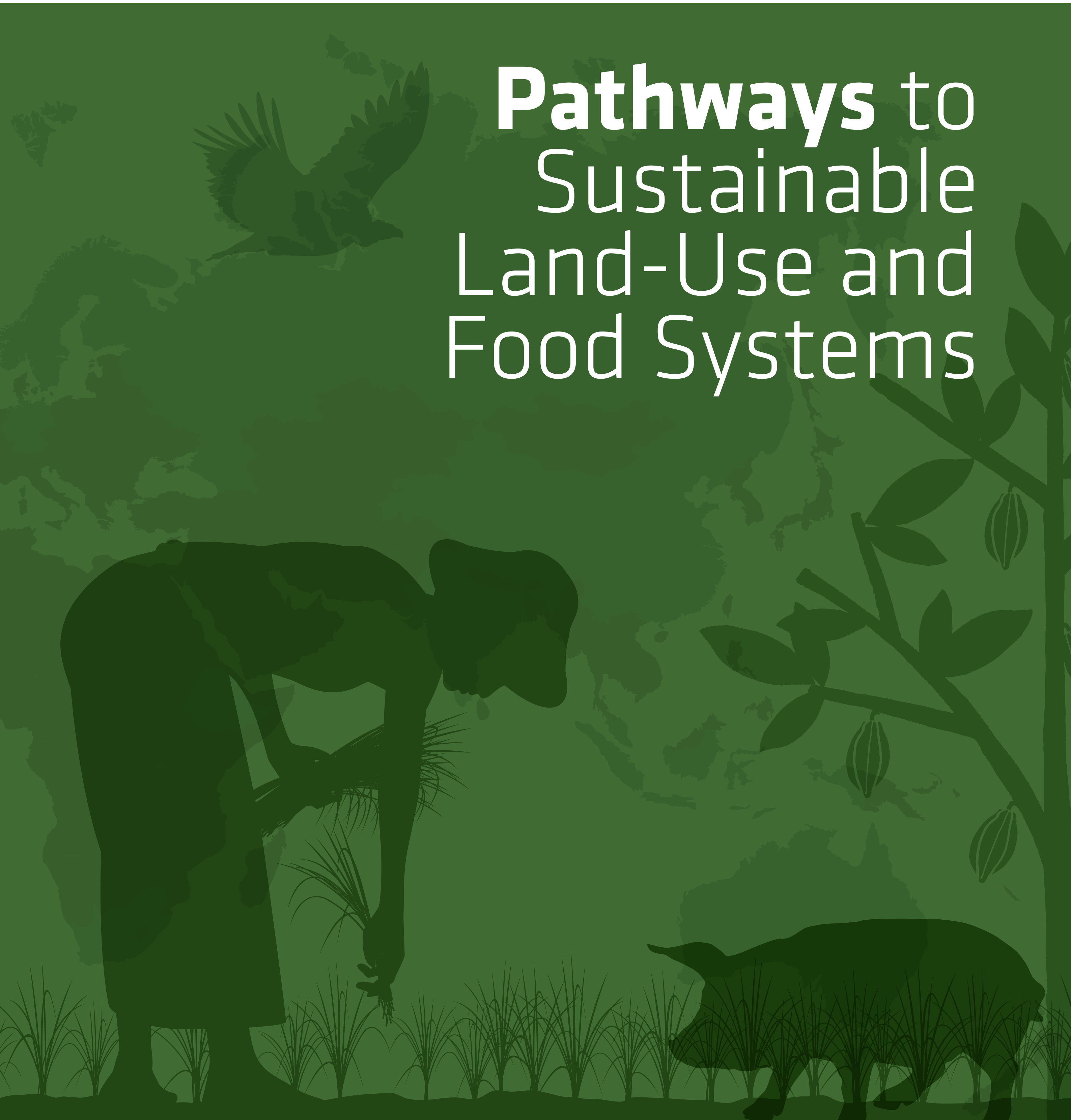
The Food and Land Use Coalition

2020 Report of the FABLE Consortium

Pathways to Sustainable Land-Use and Food Systems



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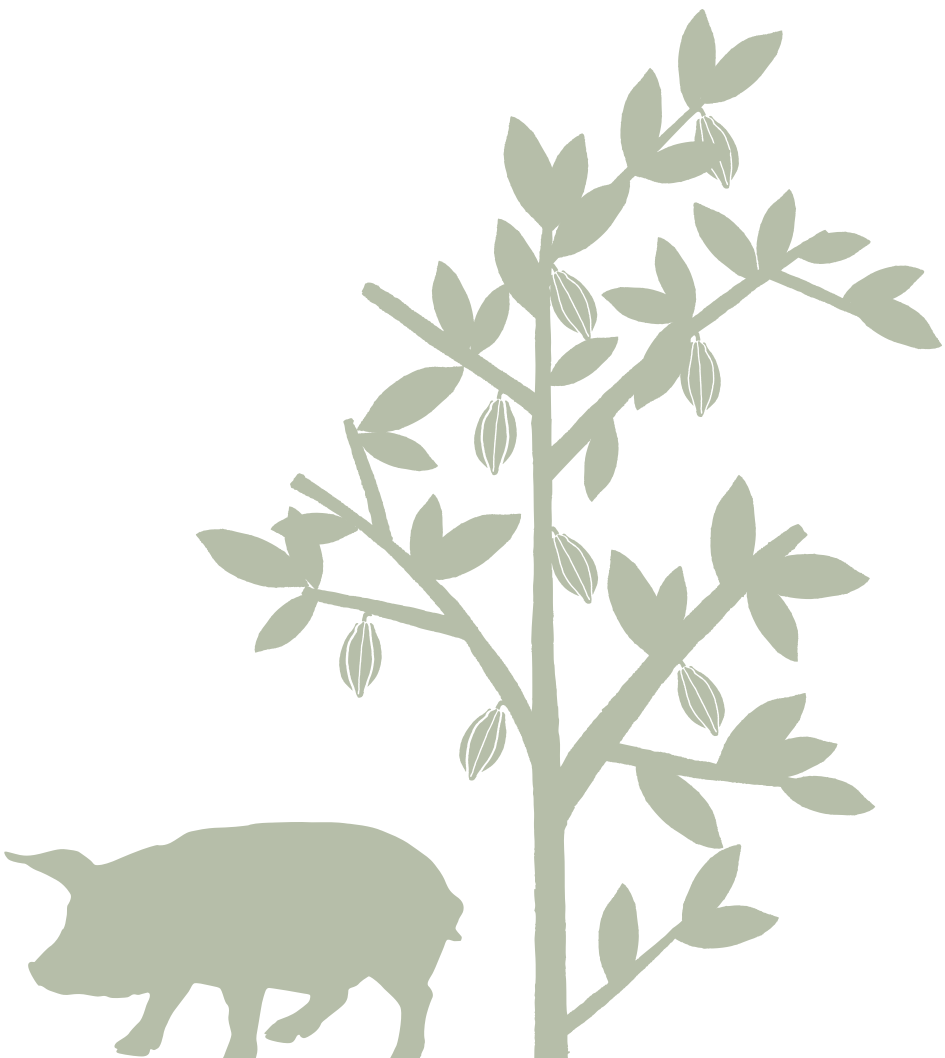
2020 Report of the FABLE Consortium

Pathways to Sustainable Land-Use and Food Systems in Australia by 2050



Australia

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This chapter of the 2020 Report of the FABLE Consortium *Pathways to Sustainable Land-Use and Food Systems* outlines options for sustainable food and land-use systems to contribute to achieving sustainable development priorities in Australia. It presents two potential pathways for food and land-use systems for the period 2020-2050: Current Trends and Sustainable Pathways. These pathways examine the trade-offs between achieving the FABLE Targets under limited land availability and constraints to balance supply and demand at national and global levels. We developed these pathways in consultation with national stakeholders and experts, including from The Commonwealth Scientific and Industrial Research Organisation (CSIRO), and modeled them with the FABLE Calculator (Mosnier, Penescu, Thomson, and Perez-Guzman, 2019). See Annex 1 for more details on the adaptation of the model to the national context. Ongoing work as part of the Australian Land Use Futures initiative[1] will undertake geospatially explicit analysis and more extensive consultation with Australian stakeholders to develop more detailed sustainability pathways for the sector.

1 https://www.climateworksaustralia.org/project/land-use-futures/

Climate and Biodiversity Strategies and Current Commitments

Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, are essential tools for achieving emission reductions. Countries' biodiversity and climate strategies under the two Conventions should, therefore, develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity.

Table 1 summarizes how Australia's Nationally Determined Contribution (NDC) relate to the FABLE domains. According to the NDC, Australia has committed to reducing its GHG emissions by 26% to 28% by 2030 compared to 2005. This includes emission reduction efforts from agriculture, forestry, and other land use (AFOLU). Under its current commitments to the UNFCCC, Australia does not mention biodiversity conservation.

Mitigation measures from agriculture and land-use change currently included in the Australian Climate Solutions Fund (Australian Government, 2020) are:

- Animal effluent management
- Beef cattle herd management
- Estimating sequestration of carbon in soil using default values
- Fertilizer use efficiency in irrigated cotton
- Measurement of soil carbon sequestration in agricultural systems
- Reducing GHG emissions in beef cattle through feeding nitrate-containing supplements
- Reducing GHG emissions in milking cows through dietary feeding additives
- Avoid clearing of native regrowth
- Avoid deforestation
- Designated Verified Carbon Standard (VCS) projects
- Human-induced regeneration of a permanent even-aged native forest
- Measurement-based methods for new farm forestry plantations
- Native forest from managed regrowth
- Plantation forestry
- Reforestation and afforestation
- Reforestation by environmental or mallee plantings
- Savanna fire management (GHG emissions avoidance)
- Savanna fire management (GHG sequestration and emissions avoidance)

Table 2 provides an overview of the biodiversity targets included in the 2010 National Biodiversity Strategies and Action Plan (NBSAP), as listed on the CBD website (CBD, 2020), which are related to the FABLE biodiversity targets (Natural Resource Management Ministerial Council, 2010). In comparison with the FABLE Targets, Australia's NBSAPs targets are less ambitious and have shorter timeframes for implementation.

Table 1 | Summary of the mitigation target, sectoral coverage, and direct references to AFOLU, biodiversity, spatially-explicit planning, and other FABLE targets in current NDC

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)*	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[2] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
NDC (2016)	2005	N/A	2030	26% to 28% reduction	Energy; Industrial processes and product use; Agriculture; Land-use, land-use change and forestry; Waste	N	N	N	N/A

Note. "Total GHG Mitigation" and "Mitigation Measures Related to AFOLU" columns are adapted from IGES NDC Database (Hattori, 2019)
Source. Australia (2015)

Table 2 | Overview of the latest NBSAP targets in relation to FABLE targets

NBSAP Target	FABLE Target
(4) **By 2015, achieve a national increase of 600,000 km² of native habitat managed primarily for biodiversity conservation across terrestrial [...] environments.**	**BIODIVERSITY:** 1. No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate. 2. Protected areas cover at least 30% of global terrestrial land by 2030.
(5) **By 2015, 1,000 km² of fragmented landscapes [...] will be restored to improve ecological connectivity.**	
(7) **By 2015, reduce by at least 10% the impacts of invasive species on threatened species and ecological communities in terrestrial, aquatic and marine environments.**	

2 We follow the United Nations Development Programme (UNEP) definition, "maps that provide information that allowed planners to take action" (Cadena et al., 2019).

Brief Description of National Pathways

Among possible futures, we present two possible alternative pathways for reaching sustainable objectives, in line with the FABLE Targets, for food and land-use systems in Australia.

Our Current Trends Pathway corresponds to the continuation of trends observed over the last 20 years and assuming little change in the policy environment. It is characterized by high population growth (from 26 million in 2020 to 38 million in 2050), significant constraints on agricultural expansion, a low afforestation target, on-trend productivity increases in the agricultural sector, and no change in diets. These and other important assumptions are justified using historical data, experts' advice, and results from integrated science assessment models (see Annex 2). This Current Trends Pathway is embedded in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m^2 (RCP 6.0), or a global mean warming increase *likely* between 2°C and 3°C above pre-industrial temperatures, by 2100. Our model includes the corresponding climate change impacts on crop yields by 2050 for corn, millet, nuts, rapeseed/canola, rice, soybean, sugarcane, sunflower and wheat (see Annex 2).

Our Sustainable Pathway represents a future in which significant efforts are made to adopt sustainable policies and practices that are consistent with higher-than-trend productivity growth and corresponds to a high boundary of feasible action. Similar to the Current Trends Pathway, we assume that this future would result in high population growth and no agricultural expansion. However, the Sustainable Pathway assumes higher agricultural productivity growth, higher carbon sequestration via afforestation and regrowth, adoption of more sustainable diets, and lower blue water footprint than under the Current Trends Pathway (see Annex 2). This corresponds to a future based on the adoption and implementation of new ambitious policies that support farmers in achieving greater yields at lower environmental costs and which enable the development of negative-carbon technologies to bridge the gap between what industry can achieve in terms of emission reductions and the net-zero emissions target. This Sustainable Pathway is embedded in a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

Land and Biodiversity

Current State

In 2010-11, around 54% of the Australian landmass was used for grazing in lands with native and modified vegetation, 23% for nature conservation, 4% for cropland and horticultural activities, 2% for forestry plantings, 0.2% for urban use, and the rest were lands with minimal human use (Figure 1). Australia's intensive agricultural zone (spanning livestock, broadacre (large scale crop operations), and horticultural production) covers the south-eastern and south-western parts of the country, but high-value horticultural production is also present in the high-rainfall zones of north-east Australia. Livestock production is present throughout (except desert areas). Forest and other natural lands can also be found throughout the country. The 2016 Australia State of the Environment report (Cresswell & Murphy, 2016) found that in most jurisdictions, the status of threatened species is poor and declining due to the pressure of invasive species (particularly feral animals), habitat fragmentation and degradation, and climate change. There are concerns that current investments in biodiversity management and monitoring are inadequate considering the magnitude of such a decline in the status of many species. Past investments in biodiversity management have reported inadequate resources to monitor and measure their outcomes for long enough to demonstrate effectiveness (Cresswell & Murphy, 2016).

The FABLE Secretariat estimates that land where natural processes predominate[3] (e.g. native vegetation areas, conservation lands, and regions with minimal human use) accounted for around 89% of Australia's terrestrial land area in 2015. Ecoregion *210-Great Sandy-Tanami Desert* holds the greatest share of land where natural processes predominate (12% of total), followed by *210-Simpson Desert* (8.7% of total) and *187-Mitchell Grass Downs* (7% of total) (Table 3)[4]. However, there is a great disparity in the proportion of land where natural processes predominate within Australia's Intensive Agriculture Zone (IAZ) – corresponding approximately to the ecoregions with cropland areas great than 100kha, located in the south-east and south-west – and the rest of Australia (Bryan et al., 2015). Ecoregions within Australia's IAZ account for only 17% of the total land where natural processes predominate, and their share of land supporting biodiversity ranging from 14% to 86% with an average share of 59%. The rest of Australia accounts for 83% of the total land where natural processes predominate, with an average share of land supporting biodiversity of 99% (range 90%-100%). For context, the IAZ occupies 85.3 Mha of land (20.8% of total agricultural land in 2010). The low levels of biodiversity habitat in intensively farmed areas suggest these production areas are under-benefiting from the ecosystem services that support agricultural production (pollination, biological pest control, flood mitigation). It highlights the need for integrated farming approaches to achieve food production and biodiversity conservation targets simultaneously.

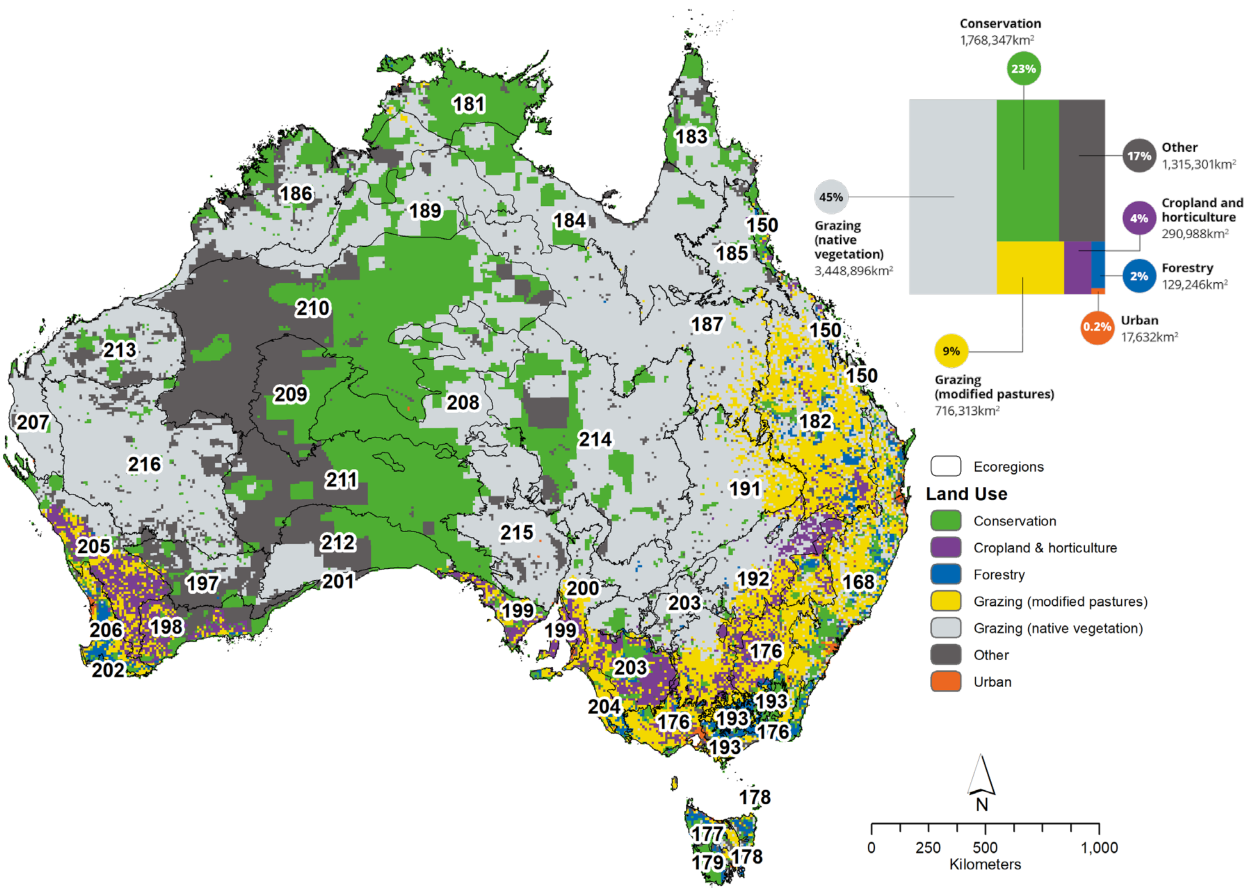
Across the country, 148 Mha of land (19% of total land) is under formal protection, falling short of the 30% zero-draft CBD post-2020 target. In ecoregions within the IAZ, 13% of the land is under formal protection (range 4-58%) compared to 22% in the rest of Australia (range 2-100%). Of all the land where natural processes predominate, 22% of it is formally protected in both the IAZ and the rest of Australia. This indicates that there has been an effort to protect areas in regions where competition for land is the strongest, and this has resulted in the equal shares reported here. Despite these efforts, it is likely that agriculture and other human activities will continue to put pressure on biodiversity and ecosystem services. Scientific, technical, behavioral, and policy innovation will be essential pillars of sustainable agricultural production.

3 We follow Jacobson, Riggio, Tait, and Baillie (2019) definition: "Landscapes that currently have low human density and impacts and are not primarily managed for human needs. These are areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages".
4 Ecoregions information were obtained from Olson et al. (2001).

Australia

In 2015, approximately 34% of Australia's cropland was in landscapes with at least 10% natural vegetation within a 1km^2 range. Outside of Australia's IAZ, this percentage increases to 83%. These relatively biodiversity-friendly croplands are most widespread in ecoregion *176-Southeast Australian Temperate Forests* (7% of total and 42% of ecoregion), followed by *192-Southeast Australia Temperate Savanna* (6.6% of total and 38% of ecoregion) and *182-Brigalow Tropical Savanna, 168-Eastern Australian Temperate Forests, 205-Southwest Australia Savanna* and *203-Murray-Darling Woodlands and Mallee* (about 3% of total each and percentages per ecoregion varying between 20-70%) (Figure 1). The regional differences in the extent of biodiversity-friendly cropland can be explained by differences in agroclimatic suitability which leads to landscape specialization into croplands and to the necessary reduction of nutrients and water available for vegetation. In ecoregions with smaller total cropland area, it is more common to have significant proportions of natural vegetation (defined here as at least 10%) within the neighborhood of crop paddocks (neighborhood defined as 1km around a paddock).

Map 1 | Land use types and ecoregions in 2010

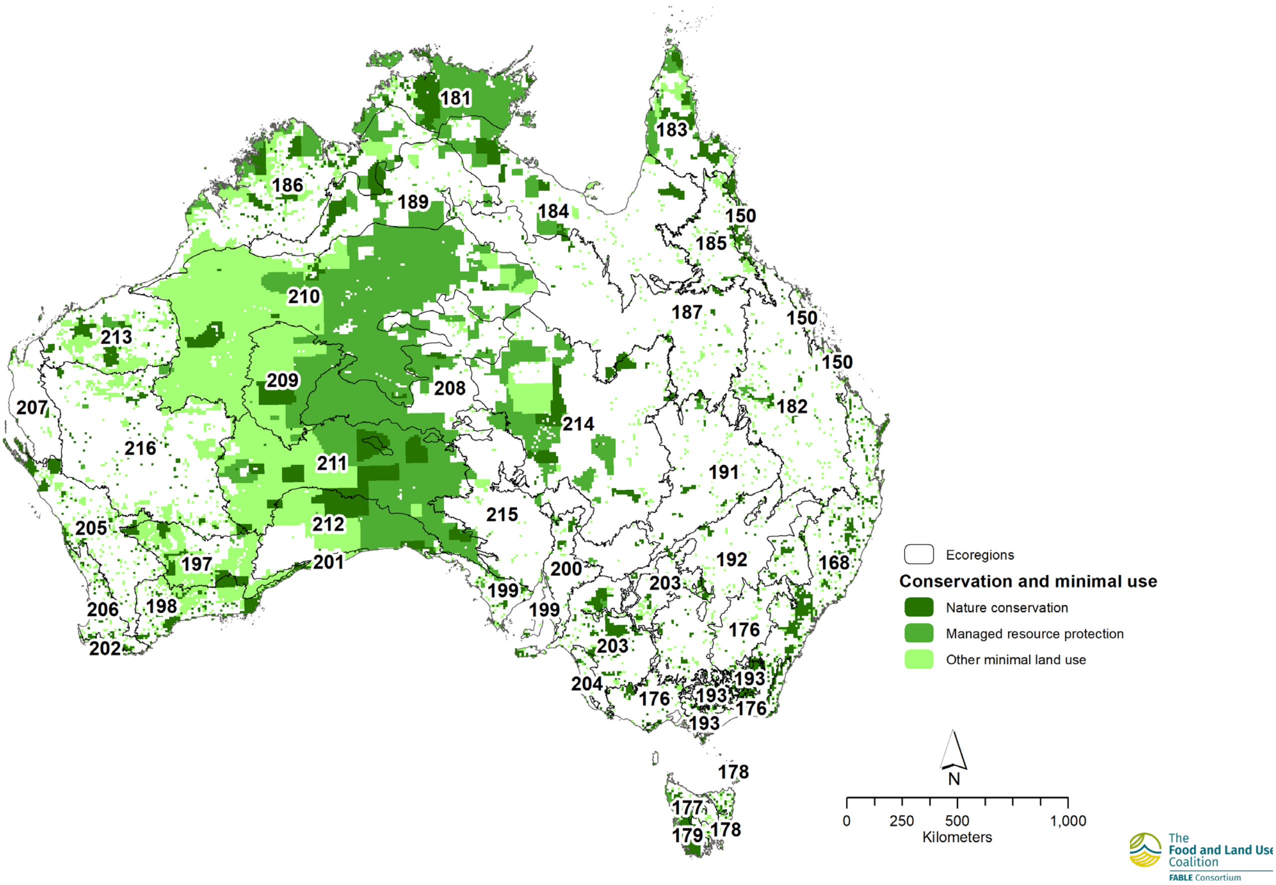


Note. Based on the Australian land use map 2010-11 (ABARES, 2016). Numbers in the map indicate ecoregions' identifiers. In this figure, conservation land corresponds to protected areas, grazing corresponds to grasslands, and the category Other corresponds to other lands with minimal human

Australia's land use

Australia's landmass extends to around 7.7 million km[2], making it the world's 6th largest country. This vast continent and its natural resources underpin Australia's economic, social, and environmental health, and support a large range of uses. Agriculture covers over half of our land and directly employs around 304,000 people across approximately 86,000 farms. In total, agriculture supports around 1.6 million direct and indirect jobs. Agriculture accounts for around 3% of Australia's gross domestic product (GDP). Over half (65%) of the food and other agricultural products produced in Australia is sent overseas. Livestock grazing on native vegetation in more arid regions makes up the largest use of agricultural land, occupying almost half of Australia's total landmass (Figure 1). After agriculture, the second largest category of land use in Australia is conservation land and minimal land use land, which together cover almost 40% of Australia's surface (Figure 2). Land with trees or shrubs planted for wood production covers around 2% of Australia. Land used most intensively for agriculture (the IAZ), is concentrated along south-western and south-eastern coasts. This area makes up just over 13% of Australia's landmass. Yet, due to its suitable climate, soil and access to markets, the area accounts for almost all agricultural production (ClimateWorks Australia, 2019).

Map 2 | Conservation and minimal use land, and ecoregions in 2010



Note. Based on the Australian land use map 2010-11 (ABARES, 2016). Numbers in the map indicate ecoregions' identifiers. Conservation land is equivalent to protected areas.

Table 3 | Overview of biodiversity indicators for the current state at the ecoregion level[5]

Zone		Ecoregion	Area (1,000 ha)	Protected Area (%)	Share of Land where Natural Processes Predominate (%)	Share of Land where Natural Processes Predominate that is Protected (%)	Share of Land where Natural Processes Predominate that is Unprotected (%)	Cropland (1,000 ha)	Share of Cropland with >10% Natural Vegetation within 1km² (%)
Rest of Australia	**210**	Great Sandy-Tanami desert	82785	38.3	99.3	38.2	61.8	0.5	100
Rest of Australia	**214**	Simpson desert	58633	21.6	99.3	21.2	78.8	5.8	81.3
Rest of Australia	**187**	Mitchell Grass Downs	47420	2.4	99.7	2.4	97.6	10.9	92.1
Rest of Australia	**216**	Western Australian Mulga shrublands	46382	4.5	99.1	4.6	95.4	5.4	99.3
Rest of Australia	**211**	Great Victoria desert	42402	30.6	99.7	30.7	69.3	28.6	53.2
Intensive Agriculture	**182**	Brigalow tropical savanna	41062	4.6	67.8	6.4	93.6	3621	48.8
Intensive Agriculture	**168**	Eastern Australian temperate forests	29553	18.9	46.9	37.6	62.4	2384	68
Intensive Agriculture	**192**	Southeast Australia temperate savanna	27869	3.8	52	6.7	93.3	10243	38.3
Intensive Agriculture	**203**	Murray-Darling woodlands and mallee	20819	17.7	53.2	31.4	68.6	7073	20.1
Intensive Agriculture	**176**	Southeast Australia temperate forests	18905	9.8	35.7	25.4	74.6	9015	41.6
Intensive Agriculture	**205**	Southeast Australia temperate forests	17799	10.6	41.2	23.7	76.3	9557	16.8

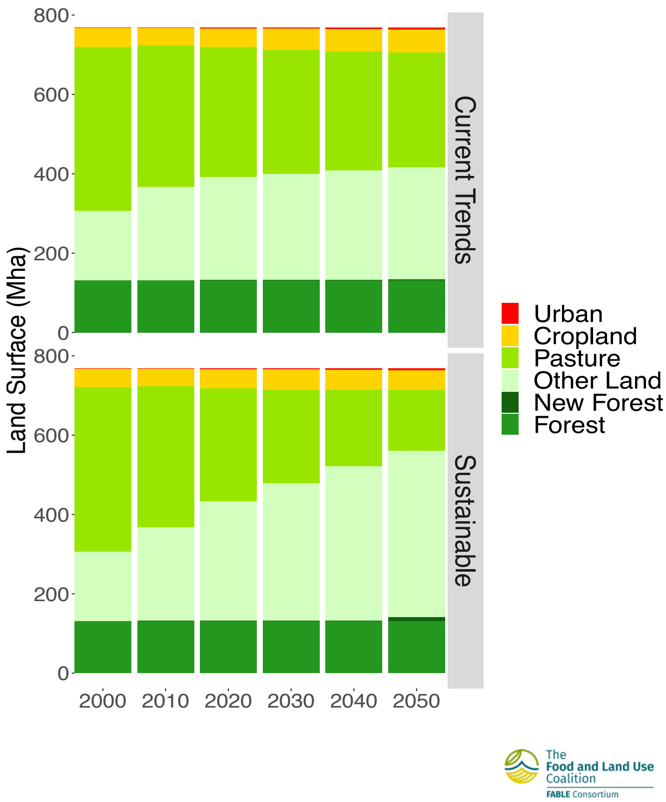
Sources. countries - GADM v3.6; ecoregions – Dinerstein et al. (2017); cropland, natural and semi-natural vegetation – ESA CCI land cover 2015 (ESA, 2017); protected areas – UNEP-WCMC and IUCN (2020); natural processes predominate comprises key biodiversity areas – BirdLife International 2019, intact forest landscapes in 2016 – Potapov et al. (2016), and low impact areas – Jacobson et al. (2019)

5 The share of land within protected areas and the share of land where natural processes predominate are percentages of the total ecoregion area (counting only the parts of the ecoregion that fall within national boundaries). The shares of land where natural processes predominate that is protected or unprotected are percentages of the total land where natural processes predominate within the ecoregion. The share of cropland with at least 10% natural vegetation is a percentage of total cropland area within the ecoregion.

Pathways and Results

Projected land use in the Current Trends Pathway is based on several assumptions, including no productive land expansion beyond its 2010 value, and 2 Mha of carbon and environmental tree plantings by 2050. By 2030, the model projects that the main changes in land cover in the Current Trends Pathway could result from an increase in other types of land cover area and a decrease of pasture area. This trend remains stable over the period 2030-2050: pasture area further decreases at an average rate of 1 Mha/yr and other types of land cover displays an expansive mirroring trend (Figure 3). By 2050, this pathway projects an expansion of croplands of 10 Mha (21%) relative to 2015: The expansion of the planted areas for pulses, cereals, sugar and fruit and vegetables explain 50%, 32%, 8%, and 2%, respectively, of total cropland expansion between 2015 and 2030. For all crops, area growth is due to the combination of a growing population with little change in domestic diets and moderate growth in crop yields on-trend with historical increases. To meet demand, area sown for crops must grow. Pasture decrease is mainly driven by increases in livestock productivity per head and ruminant density per hectare of pasture over the period 2020-2030. Abandoned pastureland is subject to vegetation regrowth, which contributes to an expansion of land where natural processes predominate by 1% by 2030 and by 3% by 2050, compared to 2010. Since this expansion is due to pasture abandonment and afforestation in more marginal lands, it is likely that the projected increase of land where natural processes predominate would occur mostly outside of Australia's Intensive Agriculture Zone (IAZ).

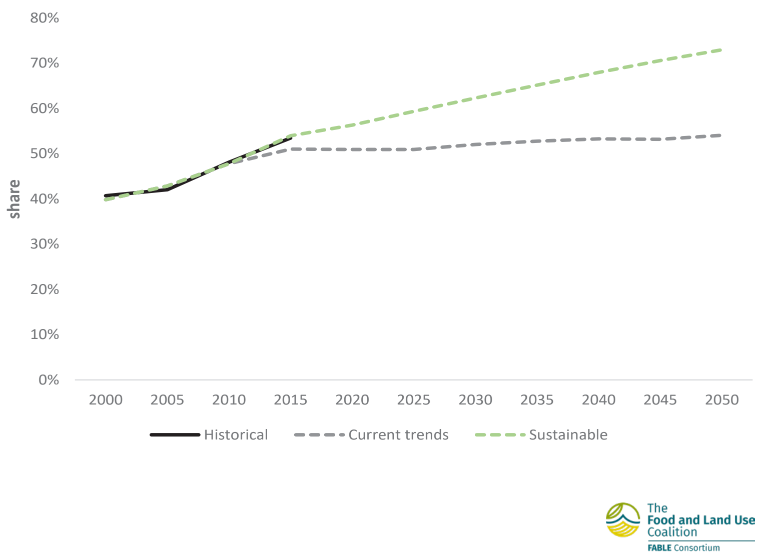
Figure 1 | Evolution of area by land cover type under each pathway



Source: Authors' computation based on FAOSTAT (FAO, 2020), ESA CCI (2017) and Land Use of Australia 2010-11 (ABARES, 2016) for the area by land cover type for 2000

In the Sustainable Pathway, the assumption on forest expansion has been changed to represent an ambitious scenario with stronger productivity growth, increasing resource-use efficiency, and overall reductions in environmental impacts. These conditions could support the Australian agriculture sector to maintain and anticipate changes in social license and enhance the resilience and competitiveness of the sector in international markets. The main difference in assumptions compared to the Current Trends Pathway includes 9.4 Mha of carbon and environmental plantations by 2050 (see Annex 2). The afforestation scenario corresponds to the lower bound of a multi-model ensemble that assessed potential Australian land-use futures under ambitious economic and environmental sustainability settings (Brinsmead et al., 2019).

Figure 2 | Evolution of the share of the terrestrial land which can support biodiversity conservation



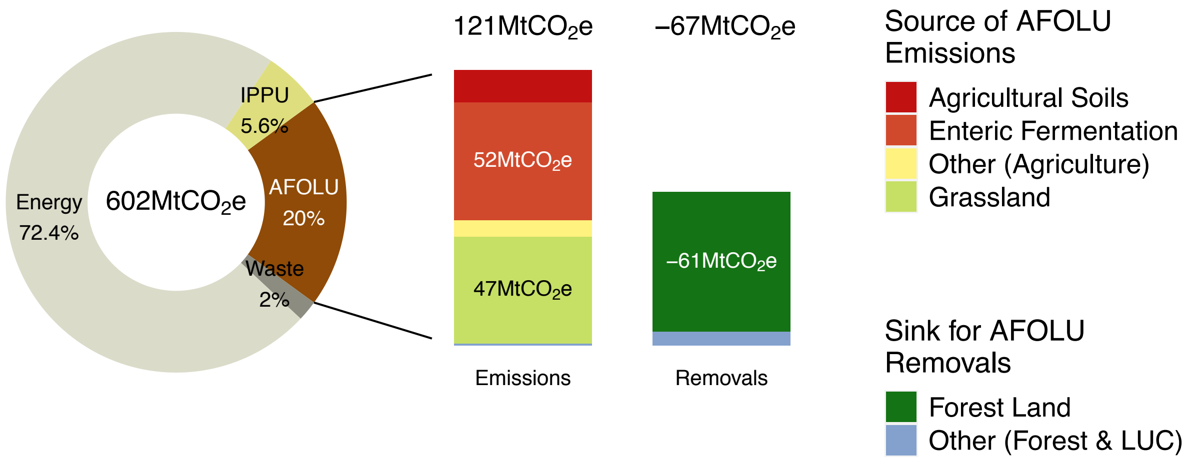
Compared to the Current Trends Pathway, we observe the following changes regarding the evolution of land cover in Australia in the Sustainable Pathway: (i) a decline of crop and pasture areas, and (ii) an increase in forest, urban and other land areas. In addition to the changes in assumptions regarding land-use planning, these changes compared to the Current Trends Pathway are explained by increased productivity growth in crops, increased livestock density growth and global changes in diets impacting the configuration of Australian landscapes. This leads to an increase in the share of the Australian landmass that can support biodiversity conservation (FABLE 2019 target) from 54% in 2015 to 73% by 2050 for the Sustainable Pathway (Figure 4). The share remains almost unchanged for the Current Trends Pathway.

GHG emissions from AFOLU

Current State

Direct GHG emissions from AFOLU accounted for 20% of total emissions in 2017 (Figure 5). Enteric fermentation is the principal source of AFOLU emissions, followed by grassland, agricultural soils, and manure management. This is due to the sheer size of the livestock industry in Australia, including approximately 25 million heads of beef cattle, 4 million heads of dairy cattle and 70 million heads of sheep in 2015 (ABS, 2017). Burning of fossil fuels to power on-farm operations, the production of farm fertilizer and pesticide inputs and their transport are estimated at 7%, 26%, and 2% of direct GHG emissions (Navarro et al., 2016) which indicates that resource use efficiency gains in Australia's agriculture sector could influence significantly more than 20% of total emissions, potentially closer to 30%.

Figure 3 | Historical share of GHG emissions from Agriculture, Forestry and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2015



Note. IPPU = Industrial Processes and Product Use
Source. Adapted from GHG National Inventory (UNFCCC, 2020)

Pathways and Results

Under the Current Trends Pathway, annual GHG emissions from AFOLU decrease from 95 Mt CO_2e/yr to 52 Mt CO_2e/yr between 2000-2020, then further decrease to 45 Mt CO_2e/yr in 2030, before declining to 25 Mt CO_2e/yr in 2050 (Figure 6). In 2050, livestock is the largest source of emissions (73 Mt CO_2e/yr) while afforestation and regeneration act as a sinks (-31 Mt CO_2e/yr and -36 Mt CO_2e/yr, respectively). Over the period 2020-2050, the strongest relative increase in GHG emissions is computed for croplands (43%) while a reduction is computed for livestock (2%).

In comparison, the AFOLU GHG emissions in 2050 in the Sustainable Pathway are 160 Mt CO2e/yr lower than in the Current Trends Pathway (25 Mt CO_2e/yr in the Current Trends Pathway, -135 Mt CO_2e/yr in Sustainable Pathway)(Figure 7). The potential emissions reductions under the Sustainable Pathway is dominated by a reduction in GHG emissions from livestock and crops (25% reduction on both) resulting from increasing crop and livestock productivity, increasing livestock density, and international shifts in diets. Compared to national commitments under UNFCCC (Table 1), our results show that AFOLU could contribute 26-43% of Australia's total GHG emissions reduction objective by 2030.

Figure 4 | Potential AFOLU emissions reductions by 2050 by trajectory compared to Current Trends

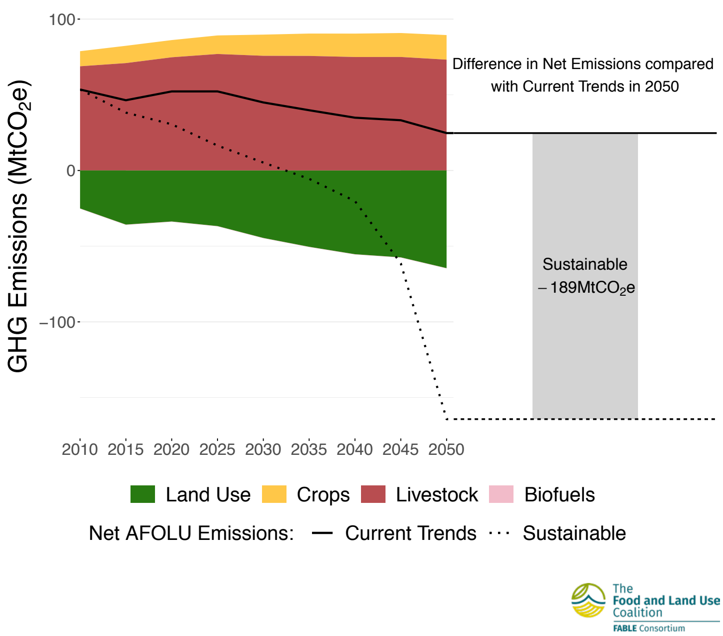
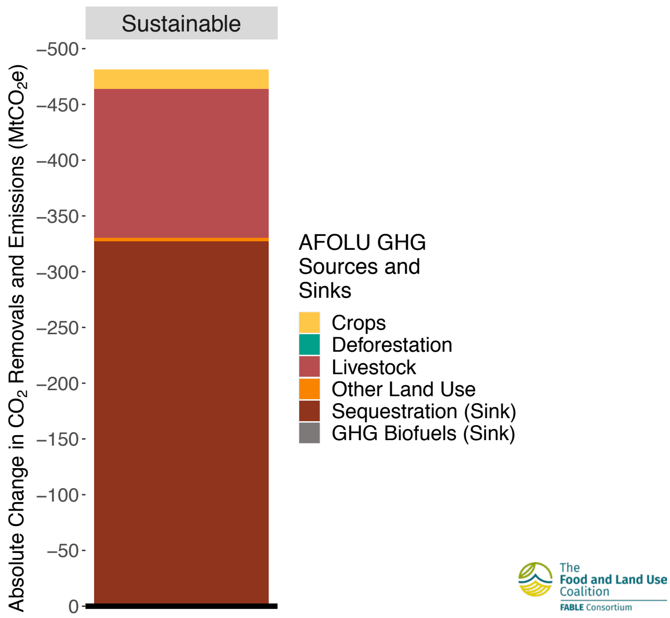


Figure 5 | Comparison of cumulated projected GHG emissions reduction over 2020-2050 by AFOLU type compared to the Current Trends Pathway



Food Security

Current State at the National Level

The Burden of Malnutrition and Overweight/Obesity

Malnutrition

Malnutrition is common in Australia. This is primarily due to micronutrient deficiencies, although certain groups are more at risk (including First Nations people who are addressed below). Specifically, up to 50% of older Australians are at risk of malnutrition or malnourished (Healdirect.gov.au, 2019), and up to 40% of all hospital admissions result in hospital-acquired malnutrition (Australian Commission on Safety and Quality in Health Care, 2019)

9.1% of women of reproductive age, 20.1% of pregnant women, and 14% of children suffered from anemia in 2016, which can lead to maternal death (WHO, 2020).

3% of children under five years suffered nutritional deficiencies in 2017 (range 2.2%-4%) (The Lancet, 2017). Most children are not eating enough fruit and vegetables, and most older girls (9-16) are not drinking enough milk (Australian Institute of Health and Welfare, 2012)

There are still major concerns around the very low intake of fresh fruit and vegetables - Most Australian (91%) do not meet their recommended minimum number of servings of vegetables, while only 50% consume enough fruit (NHMRC, 2013).

Overweight/ Obesity

36% of adults were overweight, and 31% of adults were obese in 2017-18. Obesity shares have increased from 19% since 1995. 25% of children were overweight or obese in 2017-18 (Australian Institute of Health and Welfare, 2019).

Disease Burden due to Dietary Risks

An estimated 15% of premature deaths are attributable to dietary risks (13.4-16.7%), or 106 deaths/yr (per 100,000 people) (92-123) (The Lancet, 2017).

Dietary risks are also estimated to lead to/cause 420 (364-490) thousand disability-adjusted life years (DALYs), or 342 (296-397) thousand years of healthy life lost (YLL) due to an inadequate diet (*The Lancet,* 2017). This equates to 0.02 DALYs or 0.013 YLLs per capita.

An estimated 0.06% (0.05%-0.07%) of the population (14,760 people) suffers from type 2 diabetes, and 0.29% (0.27-0.31) (71,300 people) from cardiovascular diseases; both are associated with lifestyle risk factors such as diet, but also have strong genetic risk factors (*The Lancet,* 2017).

Current State of First Nations People

The above statistics do not reflect the disparity between the population average and disadvantaged groups like Indigenous Australians and low socio-economic groups. McKay et al. (2019) found a prevalence of food insecurity is significantly affected by the type of question being asked when surveying insecurity, and also varied greatly between the general population and other disadvantaged groups such as First Nations People. For example, while the prevalence of food insecurity in the general population can vary between 1.6-8% using the single-item measure, other methodologies such as the USDA Household Food Security Survey Module measure (USDA, 2019) or the Kleve et al. (2018) Household Food and Nutrition Security Survey (HFNSS) measure observe the prevalence of 29% and 57% respectively. Disadvantaged groups (including First Nations People) in urban locations have an estimated food-insecurity of 16-25% using the single-item measure (that's on average 4.3 times greater than the general population), whereas food insecurity amongst remote First Nations People has been estimated at 76% using the single-item measure (on average 18 times greater than the general population (McKay et al., 2019). The 2016 Australian Burden of Disease Study (Australian Institute of Health and Welfare, 2019) shows First Nations People experience a burden of disease 2.3 times greater than that of non-First Nations People, and that about 37% of this burden was preventable by modifying risk factors including tobacco/alcohol use (20% of burden), and high BMI/physical inactivity/diet (24%).

Table 4 | Daily average fats, proteins and kilocalories intake under the Current Trends and Sustainable Pathways in 2030 and 2050

	2010	2030		2050	
	Historical Diet (FAO)	Current Trends	Sustainable	Current Trends	Sustainable
Kilocalories (MDER)	2,852 (2,091)	3,122 (2,081)	2,573 (2,078)	3304 (2,081)	2,259 (2,078)
Fats (g) (recommended range	138 (63-95)	150 (69-104)	118 (57-86)	158 (73-110)	95 (50-75)
Proteins (g) (recommended range	90 (71-250)	101 (78-273)	83 (64-225)	110 (83-289)	77 (56-198)

Notes. Minimum Dietary Energy Requirement (MDER) is computed as a weighted average of energy requirement per sex, age class, and activity level (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) and the population projections by sex and age class (UN DESA, 2017) following the FAO methodology (Wanner et al., 2014). For fats, the dietary reference intake is 20% to 30% of kilocalories consumption. For proteins, the dietary reference intake is 10% to 35% of kilocalories consumption. The recommended range in grams has been computed using 9 kcal/g of fats and 4kcal/g of proteins.

Pathways and Results

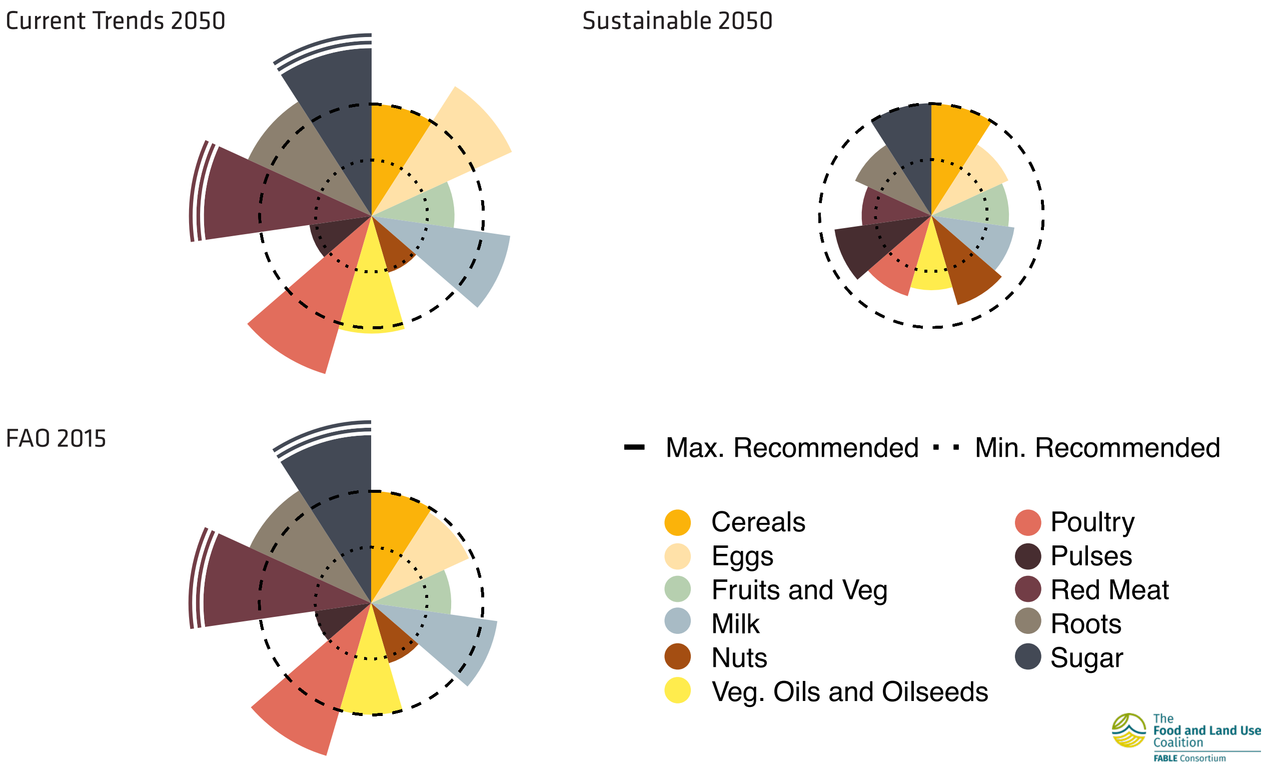
Under the Current Trends Pathway, the average calorie intake is 50% and 59% higher in 2030 and 2050, respectively, than the average Minimum Dietary Energy Requirement (MDER) (Table 4). The average calorie intake in 2010 was mainly composed of oil and animal fat (24%), cereals (19%), sugars (14%), and red meats (6%) for an aggregated 63% of the total calorie intake. Projected diet changes indicate that the consumption of animal products could increase by about 20% between 2010 and 2050. Average diet estimates indicate per capita overconsumption of red meat, poultry, roots, sugars, fish, and eggs by 2050; other food categories are within the EAT-*Lancet* healthy diet recommended ranges (Figure 8).

Under the Sustainable Pathway, we assume that domestic diets would transition towards an overall healthy diet (based on the EAT-Lancet report (Willett et al., 2019) but adapted to Australian conditions. The average calorie intake is 24% and 9% higher than the MDER in 2030 and 2050, respectively. Compared to the EAT-*Lancet* healthy diet recommendations, by 2050, under the Sustainable Pathway, only fish consumption is above the recommended range (Figure

8). However, estimates for such commodities are still under calibration in the FABLE Calculator. All other crops and animal commodities are within the recommended range of a healthy diet.

Current climate change mitigation policies in Australia still largely concentrate on reducing emissions from the energy and industry sectors (Brinsmead et al., 2019). While there are some important schemes and attempts to also reduce emissions and improve the resource use efficiency in the agricultural and land-use sectors, e.g. the Australian Emission Reduction Fund (Australian Government, 2020), these have yet to be combined with incentives to promote healthier and more sustainable diets and to achieve significant reductions in household waste. This could reduce resource use and emissions associated with domestic consumption. Some recent trends towards more plant-based eating are encouraging, as seen in a 1.5% (from 9.7% to 11.2%) rise from 2012 to 2016 in the number of vegetarians (Roy Morgan, 2019), as well as the increasing number of people reducing their red meat consumption in favor of more non-animal sources of protein (Waldhuter, 2017). However, the main challenge is that Australians at present consume high-calorie diets with very high amounts of meat, with the current average consumption for red meat estimated to be 24% higher than the maximum recommended intake in the Australian Dietary Guidelines (ADGs) (NHMRC, 2013). Introducing stronger sustainability principles in the upcoming iteration of the ADGs, along with strong monetary incentives to push consumption patterns towards more sustainable diets, could accelerate ongoing positive trends.

Figure 6 | Comparison of the computed daily average kilocalories intake per capita per food category across pathways in 2050 with the EAT-Lancet recommendations



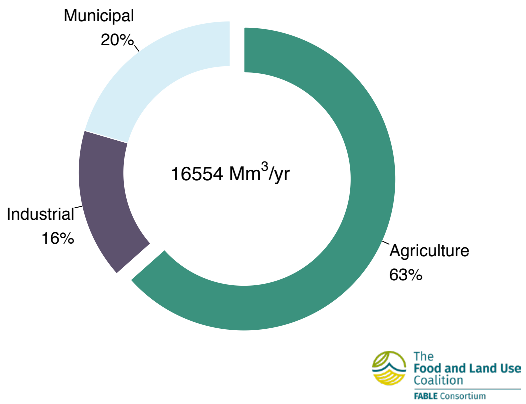
Notes. These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings), i.e. different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring, and if it is higher it is displayed on the maximum ring. The discontinuous lines for some food groups indicate that the average kcal consumption for such a group is significantly higher than the maximum recommended. The discontinuous lines that appear at the outer edge of sugar and red meat indicate that the average kilocalorie consumption of these food categories is significantly higher than the maximum recommended.

Water

Current State

The agricultural sector accounted for 63% of domestic water withdrawals in 2017 (Figure 9). In 2011, around 0.46% of the domestic agricultural land was irrigated, representing around 0.26% of the Australian landmass (ABARES, 2016). Irrigated land produces around a third of the agricultural sector's economic value. During the harvest period 2017-2018, around 9.7 million megaliters (ML) of water were used to irrigate crops and pastures in around 2.3Mha of agricultural land. Crops accounted for 69% of the total water use, and the remaining proportion was applied in pastures. The three crops with the largest water use were cotton, sugar cane, and rice, which accounted for 29%, 10%, and 8% of the total irrigation water and for 16%, 9%, and 3% of the total irrigated area, respectively (ABS, 2019c). Australia exported around 95% of its cotton production, 80-85% of its raw sugar, and around 85% of rice in 2019 (Department of Agriculture, 2019).

Figure 7 | Water withdrawals by sector in 2016

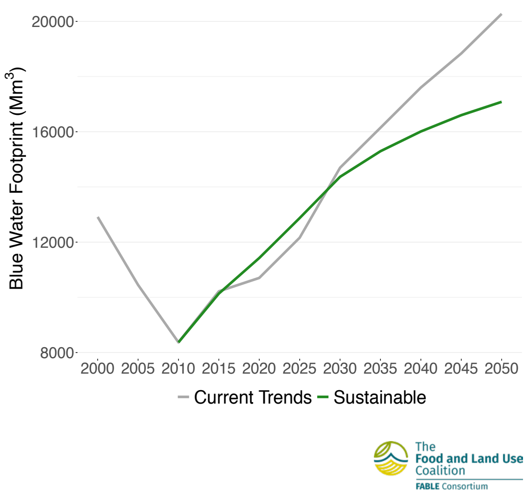


Source. Adapted from AQUASTAT Database (FAO, 2017)

Pathways and Results

Annual blue water use decreased from 12,900 Mm^3/yr to 8,400 Mm^3/yr between 2000 and 2010 (Figure 10). Such reductions in blue water use were in the context of extreme drought conditions in Australia. Indeed, the so-called "*Millennium drought*" observed during the 2000s is considered as the worst drought since European settlements in the country in 1788. Under the Current Trends Pathway, blue water use increases to 14,700 Mm^3/yr in 2030 and 20,300 Mm^3/yr in 2050[6]. In the Sustainable Pathway, blue water footprint in agriculture is estimated at 14,400 Mm^3/yr in 2030 and 17,100 Mm^3/yr in 2050.

Figure 8 | Evolution of blue water footprint in the Current Trends and Sustainable pathways



6 We compute the blue water footprint as the average blue fraction per tonne of product times the total production of this product. The blue water fraction per tonne comes from Mekonnen and Hoekstra (2010a, 2010b, 2011). In this study, it can only change over time because of climate change. Constraints on water availability are not taken into account.

Resilience of the Food and Land-Use System

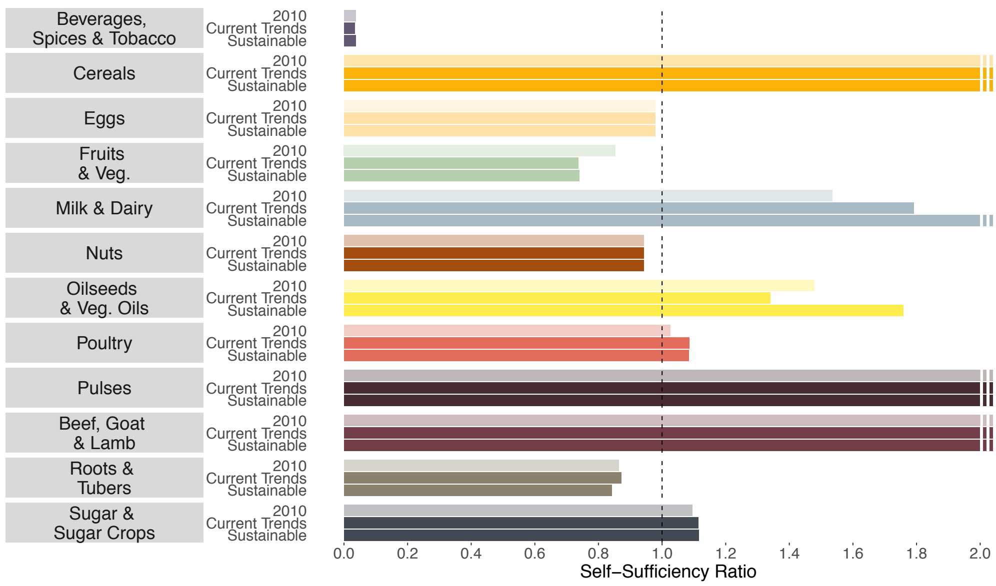
The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge Australia's resilience to agricultural-trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

Self-Sufficiency

We estimate self-sufficiency as the ratio of total internal production (tons) over total internal demand (tons). A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1. This metric is presented to facilitate the identification of Australian agricultural commodities focused on international markets. We note that importing items is not a weakness of a productive system if it allows a country to specialize in other items for which it has competitive advantages.

Under the Current Trends and Sustainable Pathways, Australia is projected to remain self-sufficient in cereals, milk and dairy, oilseeds and vegetable oils, poultry meat, pulses, beef and goat and lamb meat, and sugar and sugar crops from 2000 to 2050. Self-sufficiency increases for most product groups from 2010 – 2050 (Figure 11). The product groups that the country depends the most on and has to import to satisfy internal consumption are beverages, spices, and tobacco. This dependency remains stable during the projection period. The high increase in the self-sufficiency index for beef, goat and lamb meat is due to increases in the productivity of the livestock sector in both pathways. The increase for such a commodity group is larger in the Sustainable Pathway due to national changes in diets that result in significant reductions in the consumption of red meat.

Figure 9 | Self-sufficiency per product group in 2010 and 2050



Note. In this figure, self-sufficiency is expressed as the ratio of total internal production over total internal demand. A country is self-sufficient in a product when the ratio is equal to 1, a net exporter when higher than 1, and a net importer when lower than 1. The discontinuous lines for some food groups indicate Self-Sufficiency higher than 2. The discontinuous lines on the right side of this figure, as appear for cereals, milk and dairy, pulses, beef, goat and lamb, indicate a high level of self-sufficiency in these categories.

The Food and Land Use Coalition
FABLE Consortium

Diversity

The Herfindahl-Hirschman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

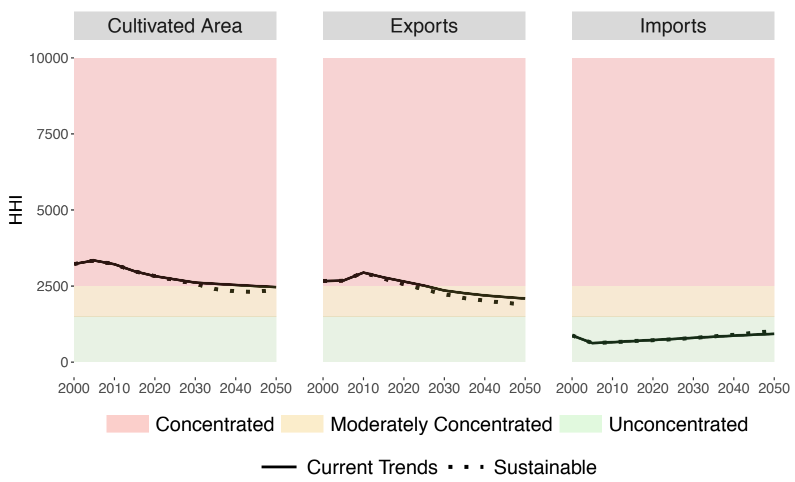
- **Cultivated area:** where concentration refers to cultivated area that is dominated by a few crops covering large shares of the total cultivated area, and diversity refers to cultivated area that is characterized by many crops with equivalent shares of the total cultivated area.
- **Exports and imports:** where concentration refers to a situation in which a few commodities represent a large share of total exported and imported quantities, and diversity refers to a situation in which many commodities account for significant shares of total exported and imported quantities.

We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, a moderate concentration between 1,500 and 2,500, and high concentration above 2,500 (Basher et al., 2013).

According to the HHI estimated from 2000 to 2015, a few commodities concentrate a large share of Australian exports (e.g. wheat, beef, wool, dairy; DFAT, 2017) which could pose some trade risks to the domestic agricultural sector if supply chains are disrupted (Figure 12). Import quantities are not concentrated, although there are concerns that in the future a much more significant percentage of fruit and vegetables will need to be imported to maintain nutritious diets (Candy et al., 2015; Ridoutt et al., 2017). The large area required for livestock production generates a concentrated HHI estimate during the historical period.

Under both the Current Trends and Sustainable Pathways, we project a gradual reduction in the concentration of exports and cultivated area across modelled commodities, reaching moderate HHI levels by 2050. The HHI of projected imports under both scenarios increased from 2005 to 2050, reaching the levels observed in 2000. This indicates a continuation of small import shares across import commodities. Reductions in the concentration of export and cultivated area across a few commodities are generated by domestic increases in agricultural productivity, livestock density, and global shifts in diets.

Figure 10 | Evolution of the diversification of the cropland area, crop imports and crop exports of the country using the Herfindahl-Hirschman Index (HHI)



Discussion and Recommendations

Australian food and fiber exports are a key driver of regional economic growth within the country and contribute to the food security of millions in the Asia-Pacific region. However, this sector faces growing global and domestic issues (e.g. climate change, trade barriers and other supply chain disruptions, changes in diets). The results suggest that there are pathways to more a sustainable and resilient Australian future with better socio-economic and environmental outcomes than under current trends. However, its achievement requires significant structural changes and coordinated interventions in several components of the domestic system to increase its resilience and environmental and socio-economic performance. Significant buy-in from key stakeholders about the need for systemic change could help drive coordinated actions to maintain the local and global relevance of the Australian agricultural and food sector.

An optimistic Sustainable Pathway, as modeled here with a high degree of technical feasibility, enables the identification of conditions needed to achieve multiple sustainability targets simultaneously. However, the robust identification of pathways towards a sustainable and resilient Australian FABLE system requires a significant level of interaction with multiple stakeholders, decision-makers, and scientists. This work is being undertaken as part of the ClimateWorks Australia Land Use Futures program. Using a participatory-based approach to scenario development, the Land Use Futures program[7] will assess sustainable future pathways for the Australian food and land use system with more robust modeling approaches and extensive stakeholder engagement to inform implementation efforts.

Results from the Australian FABLE modeled pathways indicate that a Sustainable Pathway could result in multiple environmental and economic successes. However, such a scenario appears to be at the higher bound of what is technically or socially achievable in terms of productivity increases and environmental performance. In particular, on the issue of changing diets towards those similar to the recommended EAT-Lancet diet, the current starting point for Australia is a high animal-protein intake diet, with an average of 95 kilograms per capita per year of meat intake, which is significantly more than the OECD average of 69 kilograms per capita per year (OECD, 2020). While there have been some encouraging signs of shifts towards plant-based diets, the magnitude of the shift required to achieve the EAT-Lancet diet is very high compared to the current Australian reality, already significantly higher than the generous recommended meat intake in the latest edition of the Australian Dietary Guidelines (NHMRC, 2013). Such a drastic change in diet would require significant incentives through price-based mechanisms, nutrition education campaigns and the ubiquitous availability, affordability, and palatability of alternatives.

It is also important to consider that in the case of a key food exporter such as Australia, domestic food consumption will always account for a small percentage of overall food and land-use emissions. The quest to boost exports and continue growing the agricultural sector (National Farmers Federation, 2020), will therefore always present the biggest challenge in improving the environmental performance of the food and land-use sector, in the absence of disruptive technological breakthroughs (Herrero et al., 2020). However, given Australia's role as a major food exporter, providing the option of consumption-based accounting in the FABLE Calculator to encompass resources and emissions embodied in trade (Wiedmann & Lenzen, 2018), would be a fairer way to apportion responsibility at the global scale, particularly if Australia is a more efficient producer for a given commodity compared to other major producers. Optimizing the location of agricultural production can have a significant positive impact on reducing global environmental impacts (Davis et al., 2017; West et al., 2014).

7 More information about the ClimateWorks Australia's Land Use Futures program can be found here: https://www.climateworksaustralia.org/project/land-use-futures/

The FABLE Calculator is a useful tool for quick assessments of potential global-local trade-offs associated with multi-target sustainability pathways. However, there are significant uncertainty and feasibility concerns regarding future values of key input data and parameter assumptions (e.g. changes in productivity, exports, diets). While endogenous modeling of stochastic components is always a challenging task, accounting for the compounded effect of uncertainty on sustainability targets could improve the use of the calculator for robust decision making.

As part of the Land Use Futures project, ClimateWorks Australia, CSIRO, and Deakin University are working on the next generation of high-resolution spatiotemporal modeling of Australian land use that aims to build on and expand the findings from the FABLE Calculator. Such capability is expected to inform future assessments of alternative sustainability pathways as defined through discussions with diverse stakeholder groups.

Annex 1. List of changes made to the model to adapt it to the national context

Multiple components of the FABLE Calculator were modified to adapt the analysis to Australian conditions. In addition, we generated scenarios grounded on expert consultation and peer-reviewed projections of plausible Australian futures, e.g. the Australian National Outlook (Brinsmead et al., 2019).

Some changes include:

- Projections of crop and livestock productivity (including livestock density) based on historical spatiotemporal data, statistical models, and literature review.
- Inclusion of Australian-specific Gross Domestic Product (GDP), trade, and population projection to improve the representation of domestic food demand. This was based on econometric analysis of historical data and results from integrated assessment models published in peer-reviewed studies.
- Changes in implementation rates for multiple variables, e.g. defining expected time when carbon plantings become profitable due to global climate abatement efforts impacting carbon offset prices.
- Modification of default AFOLU carbon coefficients to make them representative of Australian conditions.
- The FABLE Calculator estimates interactions and responses across environmental and economic components of the FABLE system to assess potential outcomes of possible scenarios. However, errors in input data or in the representation of how the system responds to changes in some of its drivers could impact the results. Our team developed a modeling improvement that allows estimation of the robustness of the Australian FABLE Calculator results from to errors in input data or in the representation of linkages or system responses in the model. This capability is ready to be implemented in future implementations of the Australian FABLE Calculator.

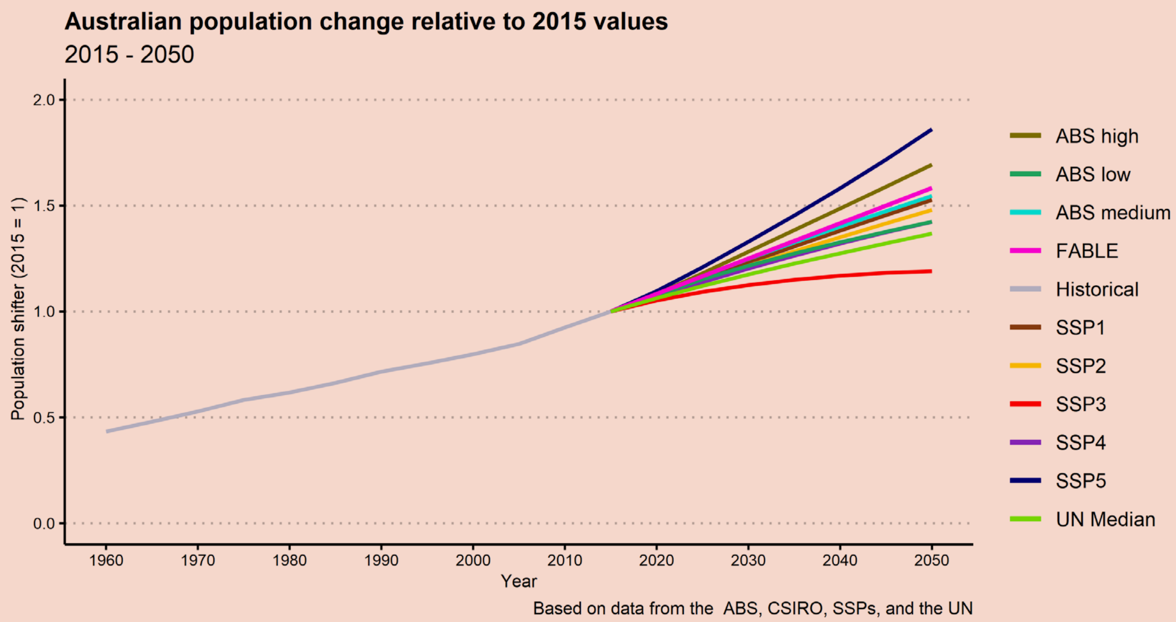
Annex 2. Underlying assumptions and justification for each pathway

POPULATION Population projection (million inhabitants)

Current Trends Pathway	Sustainable Pathway

Population : 38 million by 2050

The Australian population is expected to increase by 58% between 2015 and 2050 from 24 million to 38 million.
Net overseas migration is the main driver of Australian population growth. This parameter accounted for around two-thirds of the population increase in 2016-17 (ABS, 2019a). Population projections are based on Australian-specific assumptions of fertility, mortality, international, and domestic migration informed by historical trends (ABS, 2013).



Notes. ABS (Australian Bureau of Statistics) scenarios correspond to low, medium and high increases in the Australian population. The FABLE projection corresponds to population projections slightly larger than the ABS medium scenario generated for the Australian National Outlook 2019 (Brinsmead et al., 2019). This scenario was selected for the Current Trends and Sustainable Pathways. Population projections for all the SSPs (Shared Socioeconomic Pathways) and median projections from the UN (United Nations) are also included for comparison of the scenario selected in FABLE.

LAND Constraints on agricultural expansion

Current Trends Pathway	Sustainable Pathway

We assume that there is no productive land expansion beyond 2010 agricultural area levels for both the Current Trends and Sustainable Pathways.

Land clearing regulations combined with agricultural productivity improvements result in no expansion of the farming frontier. Farmed land in Australia has reduced from around 65% of the Australian landmass in 1973 to about 53% in 2015 (National Farmers Federation, 2020). Spatially explicit analysis of historical land cover change in Australia and projected expansion of forest cover in the country indicate a continuation of the decreasing trend of the domestic agricultural footprint (Marcos-Martinez et al., 2018, 2019). In addition, the National Farmers Federation specifies a target of maintaining Australia's total farmed land area at 2018 levels by 2030 (National Farmers Federation, 2020).

LAND Afforestation or reforestation target (1000 ha)

Current Trends Pathway	Sustainable Pathway
Continuation of current forest cover expansion trends results in 3.1 Mha of new forest or forest regrowth. High-resolution forest cover data indicate increases in forest cover within Australia's intensive agricultural region of around 342 thousand hectares per year from 2008 to 2014 (Marcos-Martinez et al., 2018). Total forest cover in Australia increased by about 0.8 Mha per year from 2011 to 2016 (Montreal Process Implementation Group for Australia and National Forest Inventory Steering Committee, 2018). Historical forest cover change trends suggest the continuation of forest expansion or regrowth during the next decades (Marcos-Martinez et al., 2019). Statistical projections of forest cover change indicate a potential increase of around 2 Mha of forest in Australia's intensive agricultural region by 2050 due to improvements in agricultural productivity, climate change impacts, and changes in input and output prices (Marcos-Martinez et al., 2019). The Australian Government, through its Emission Reduction Fund, has spent around US$1.8 billion on multiple mechanisms to offset GHG emissions and plans to spend a similar amount during the next year to achieve Paris emission reduction commitments (Clean Energy Regulator, 2019; Nong & Siriwardana, 2018). Most of the funds have been spent on human-induced regeneration of disturbed landscapes which could also contribute to increasing forest cover area in the country.	Carbon and environmental plantings increase forest area by around 10.5 Mha. Global climate change abatement action generates market incentives for carbon and environmental plantings. Such incentives combined with higher than trend increases in agricultural productivity, social license to expand forestry plantings in agricultural land, and available infrastructure to allow such expansion, generate high levels of forests plantings after 2040. 10.5 Mha of new forests by 2050 represents a 7.8% increase in Australian forest land observed in 2018. New tree plantings would cover around 1.4% of the Australian landmass. This target corresponds to a conservative estimate of the Green and Gold scenario of the Australian National Outlook 2019 (Brinsmead et al., 2019).

BIODIVERSITY Protected areas (1000 ha or % of total land)

Current Trends Pathway	Sustainable Pathway

The share of the Australian land that can support biodiversity conservation is estimated based on the default calibration of the FABLE Calculator (FABLE, 2019).

Australia

PRODUCTION Crop productivity for the key crops in the country (in t/ha)

Current Trends Pathway	Sustainable Pathway
Historical yields trends are maintained: - from 2.13 t/ ha in 2015 to 2.62 t/ha in 2050 for wheat, - from 9.85 t/ ha in 2015 to 9.2 t/ha in 2050 for grapes.	Strong historical yield declines (<-0.5%/yr) are halved (i.e. still declining but at a slower pace). Weak historical yield declines (>-0.5%/yr) are inversed (i.e. switch to growth). Historical yield increases are doubled for broadacre crops and increased by 25% (i.e. x1.25) for horticulture. - from 2.13 t/ ha in 2016 to 3.24 t/ha in 2050 for wheat, - from 9.85 t/ ha in 2016 to 10.54 t/ha in 2050 for grapes.

Our assumptions are based on a spatially explicit statistical analysis of productivity growth from 1985-2016 combined with CSIRO's productivity change projections (Brinsmead et al., 2019) that account for ambitious policy environment and significant technological improvements.

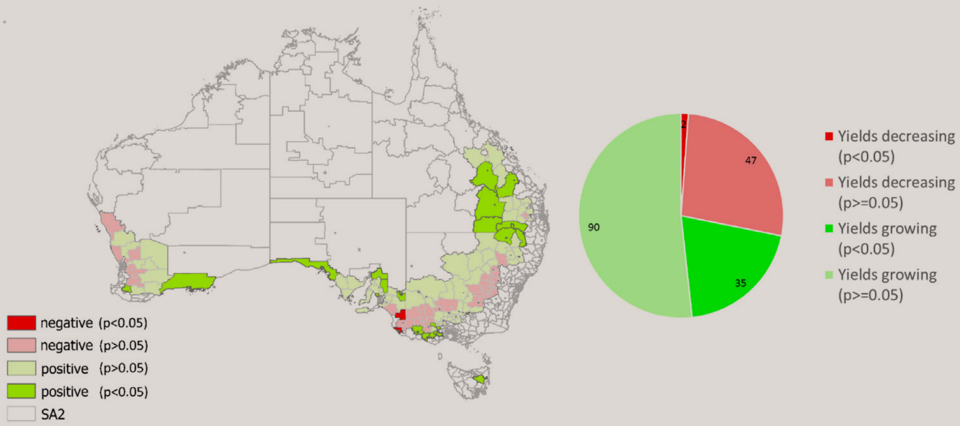
Annual agricultural production data from 1985 to 2016 (ABS, 2017) was used to investigate historical changes in average yields for each commodity. Yield comparisons were made at the local area level (SA2, the smallest spatial statistical unit during census years) for SA2s within main production areas (area sowed> 500 ha on any given year). The yield trend for each commodity-SA2 pair was modeled via linear regression of yearly yields. The regression parameters of each commodity at the national scale were derived via the area-weighted sum (total sown area per commodity over the whole period) of individual SA2-level parameters where p-score <0.05 (i.e. where regressions were statistically significant). Regressions that were not statistically significant were included in the national mix as zero growth. National estimates of yield growth were computed for the broadacre and horticulture sectors and then aggregated to national growth using 2010 revenue as weights. Revenue weights offer a more balanced picture of the relative importance of broadacre and horticultural sectors (83% and 17% of crop revenues respectively), whereas area weights would be very heavily skewed towards the broadacre sector (97% and 3% of total area 1985-2016 respectively).

Overall, annual revenue-weighted yield growth between 1985 and 2016 is estimated to be at 0.75%/yr. Average growth for broadacre crops is estimated at 0.78%/yr, whereas horticultural crops growth was weaker at 0.62%/yr. Yearly yields are highly variable as they depend on very specific climate conditions, the timing or amount of which can significantly affect yield (e.g. rainfall amount can be adequate but not occur at critical points for plant growth and development) and which only process-based models can accurately represent. This means linear models to represent growth can only explain a relatively small proportion of yield variability. Similarly, the aggregate historical growth does not mean all commodities had growing yields over time. In fact, some commodities experienced yield declines.

A visual representation of the yield trend method for wheat (see below) shows it is more likely to observe historical yield growth in wheat than yield decline at the local area (SA2) level, both when yields have varied in a statistically significant manner (35 vs 2 regions) and when yields have varied in a non-statistically significant manner (90 vs 47 regions). However, to ensure statistical robustness, we count non-statistically significant trends as zero growth. The datasets used in this analysis are consistent with Yield Gap Australia (CSIRO, 2016).

Wheat yield growth (1985-2016) linear regression slope and statistical significance (p-value)

Notes. Negative and positive refers to the direction of the linear regression slope, which indicates decreasing or increasing yields, respectively. P-value <0.5 indicates the statistical significance of the results. Yield trends with p-value > 0.05 are not statistically significant and are counted as zero-growth.



Aggregate (revenue-weighted) productivity changes:

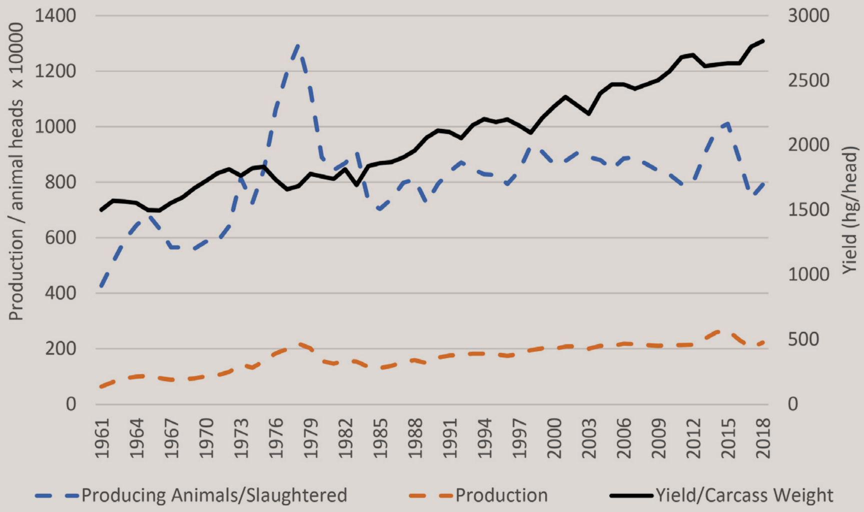
Industry	Revenue weight	Weighted growth BAU	Weighted growth sustainability
Broadacre (large scale crop operations)	83%	0.78%	1.59%
Horticulture	17%	0.62%	1.12%
All		0.75%	1.51%

PRODUCTION Livestock productivity for the key livestock products in the country (in t/head of animal unit)

1.5%/yr livestock productivity growth.

Livestock productivity growth over the last few decades has likely been >1%. Future livestock productivity (kg per animal) growth of 1.5%/yr is feasible (Dr. Toni Reverter - Senior CSIRO scientist in computational and systems biology in livestock systems, personal communication, 2020). Low hanging fruits in terms of productivity growth involve increasing the number of cattle that are finished in feedlots and/or the time cattle spend in feedlots. Historical livestock production data from FAO indicate a national average growth of beef productivity (between 1985-2018) of 1.25% per annum, which further supports this parameter value).

Beef production statistics, Australia 1961-2018 (FAOSTAT, 2019)



PRODUCTION Pasture stocking rate (in number of animal heads or animal units/ha pasture)

21% increase in livestock density between 2015 and 2050, 90% of which occurring by 2030 and slowing down from there onwards. This is equivalent to a 0.5% linear growth per year.

Baseline data obtained from historical livestock heads and FAO pasture areas contained in the FABLE Calculator. ABARES farm survey data for specialist beef, specialist sheep and dairy industries (ABARES, 2020) were used to validate the order of magnitude of our assumption. We calculated livestock density using reported values of heads per farm and average hectares per farm, for every year from 1985 to 2015 and by ABARES region (ABARES, 2020). The estimated historical average growth in livestock density using this method is 0.3%/yr, which is in the same order of magnitude as the adopted parameter.

33% increase in livestock density between 2015 and 2050, 90% of which occurring by 2030 and slowing down from there onwards. This is equivalent to a 0.82% linear growth per year and is a midpoint between current trends growth and doubling the current trend. This could be achieved by increasing the number of cattle being finished in feedlots, by increasing the time cattle spend in feedlots, or via an intermediate solution.

Further increases to livestock productivity could be achieved by extending the current typical period livestock spend in feedlots (30 days) to 60 or even 90 days (Dr Toni Reverter, pers. comm.). The Australian Lot Feeders' Association (Australian Lot Feeders' Association, 2019) states the typical time spent in feedlots is 50-120 days or 10-15% of cattle's lifetime. Above-average livestock productivity growth in this scenario is associated with an increase in livestock density resulting from more cattle spending longer in feedlots.
Livestock density growth would have two positive environmental effects: 1) reduce the amount of land required for pasture and, 2) increase the amount of GHG emissions that could be mitigated through FutureFeed[8] supplementation. Current (conservative) estimates for FutureFeed towards 2030 are to produce around 7000 tons of dry weight seaweed supply to around 200,000 animals, resulting in 300,000 tons of CO2 abated by 2030, or up to 3 million tons of CO2 (Michael Battaglia, CEO of Future Feed, pers. comm.).

8 FutureFeed is a livestock feed supplement which can increase production and reduce methane emissions (https://research.csiro.au/futurefeed/).

PRODUCTION Post-harvest losses

Continuation of post-harvest loss rates observed from 1961 to 2014.

FAO's data indicates that Australia's post-harvest losses have been historically marginal oscillating at around 0.69% for crops and 0.05% for livestock production. The Current Trends Pathway assumes that such rates are constant to 2050.

We assume a 30% reduction in post-harvest losses by 2050 relative to average historical levels.

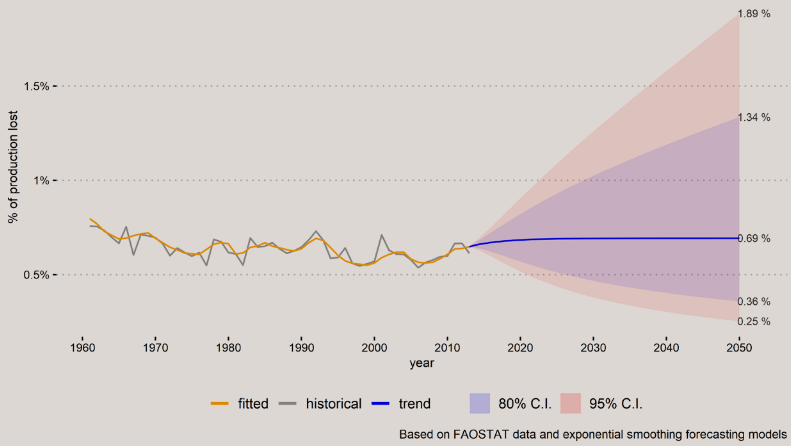
This target is consistent with historical post-harvest losses trends observed through statistical analysis of FAO data (FAOSTAT, 2019).

The National Farmers Federation has set a target of 50% reduction in food waste throughout the value chain by 2030 (National Farmers Federation, 2020). Reductions in Australia's freight costs are of significant relevance to achieve such a target and to improve the international competitiveness of the domestic agricultural sector. The CSIRO's Transport Network Strategic Investment Tool (TraNSIT) estimates potential freight savings (on-road costs and labor) from road upgrades to be between 1% and 5% (Higgins et al., 2015). TranNSIT does not quantify potential gains that reduced travel time could have on produce quality, increased shelf-life of perishable items, and potential price premiums for fresher produce.
If industries realize this opportunity and increase capital investment in the quality of their logistics chain (RIRDC, 2020) (as opposed to relying on cheaper transport for improved gross margin), product quality and shelf life could improve, pushing post-harvest losses down, and reducing household food waste.

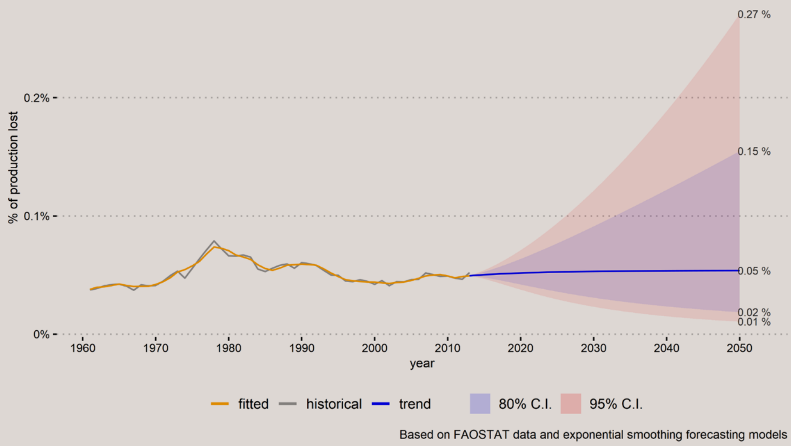
The FAO defines post-harvest losses as the amount of a commodity wasted during its storage and transportation from farm gate to the household. This metric excludes losses before and during harvest and household waste.

FAO data (FAOSTAT, 2019), and exponential smoothing forecasting models for time series data (Hyndman et al., 2002) were used to investigate historical trends in the share of crop and livestock production lost during storage and transportation.

Share of crop production lost during storage and transportation
1961 - 2050



Share of livestock production lost during storage and transportation
1961 - 2050

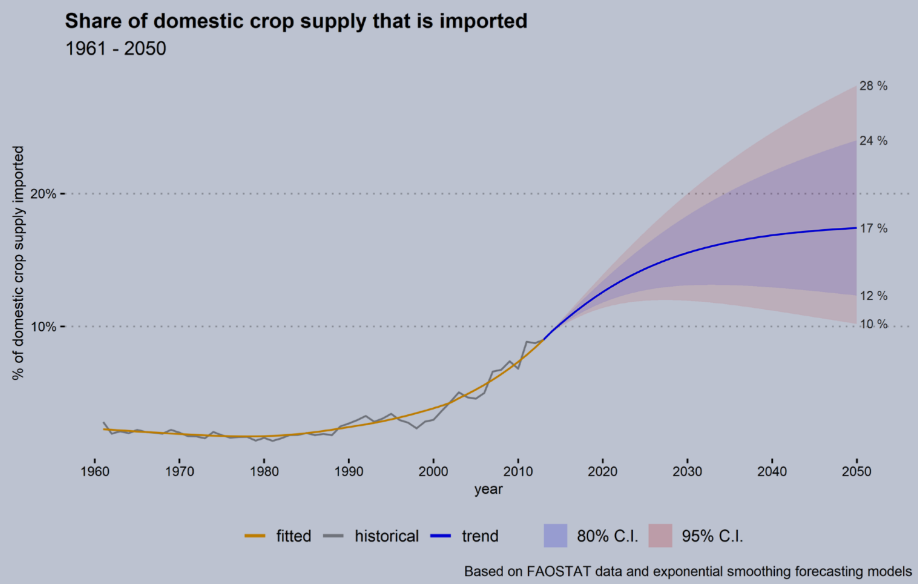


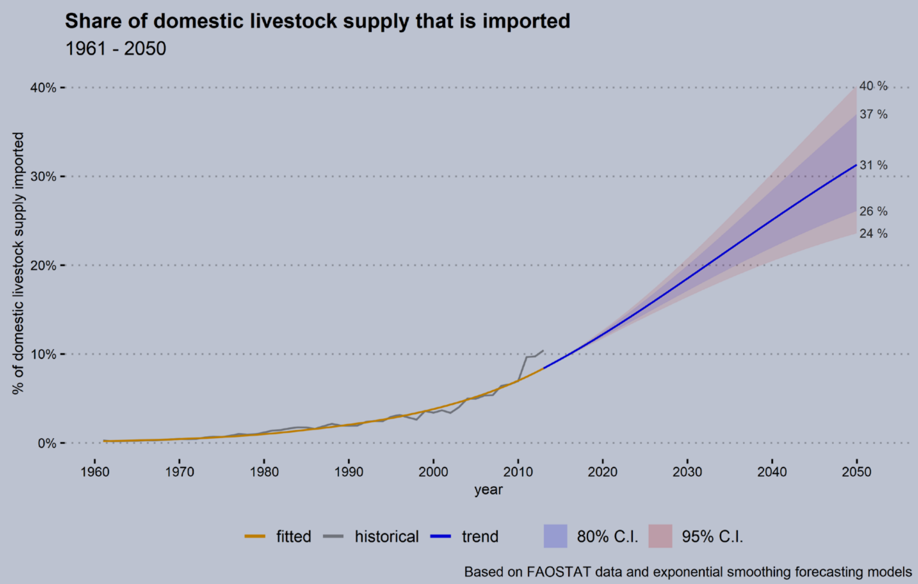
TRADE Share of consumption which is imported for key imported products (%)

Current Trends Pathway	Sustainable Pathway

Increasing imports. The proportion of the domestic consumption that is imported doubles between 2000 and 2050.

The annual share of the domestic crop and livestock consumption that is imported was 2% and 1% from 1961 to 2000, on average. By 2013, such share increased to around 9% for crops and 3% for livestock. Trend analysis indicates that by 2050 the share of imports to fulfil internal consumption could reach around six times the share observed in 2000 for crops and nine times the share of livestock imports. Historical trends suggest a larger dependence on imports to satisfy domestic consumption than assumed in the Australian FABLE Calculator. A conservative scenario was selected under the assumption that changes in agricultural productivity and domestic diets could diminish Australian food import volumes.

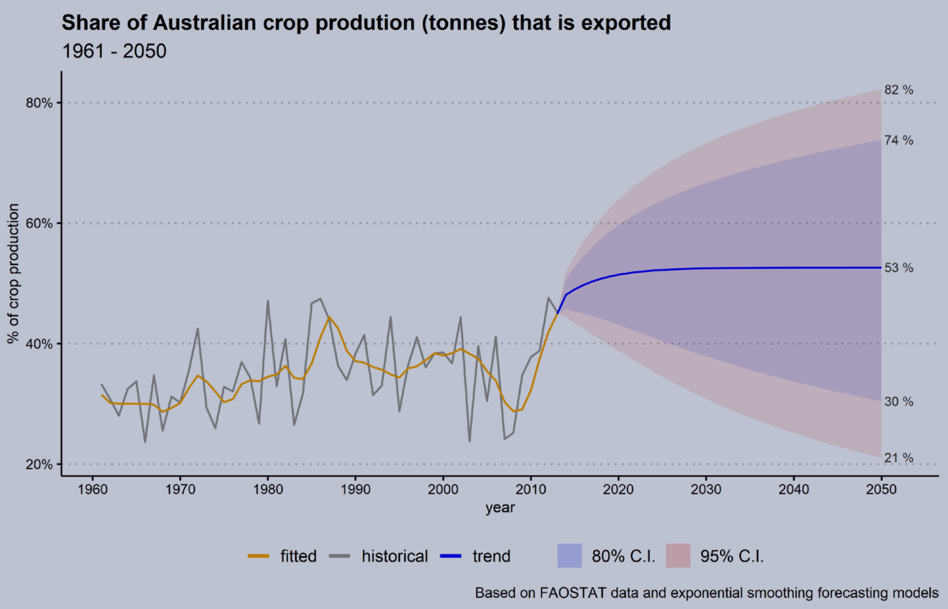


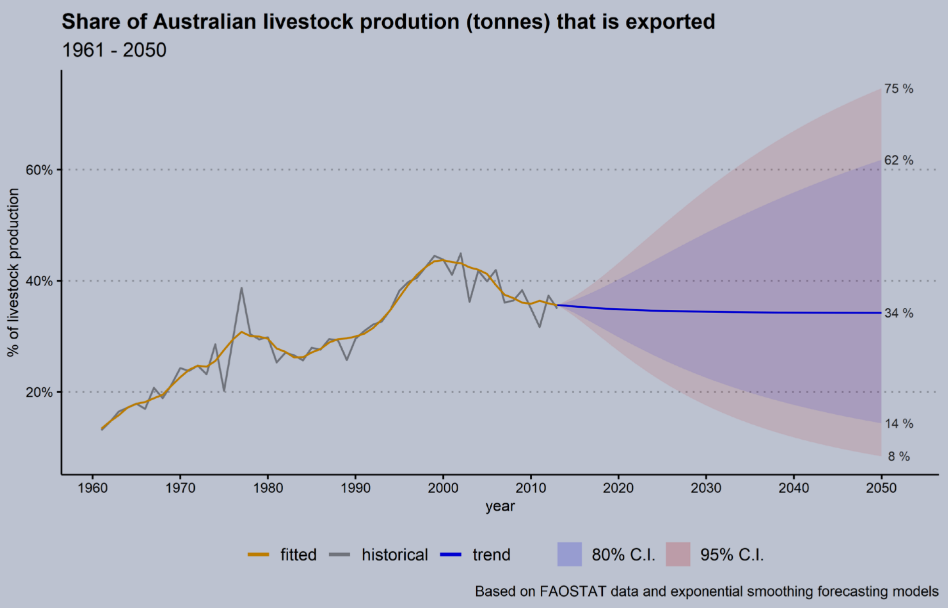


TRADE Evolution of exports for key exported products (1000 tons)

Increasing exports. By 2050 export quantity for crops is two times the levels observed in 2000, and 2.4 times for livestock products.

The selected export targets are based on projections from a multi-sector assessment of plausible Australian economic and environmental futures (Brinsmead et al., 2019). On average, around one-third of the Australian crop production was exported between 1961 and 2000. After 2010, crop exports have been above the historical average, reaching 45% of the crop production by 2013. However, in terms of weight, Australian crop exports in 2013 were only 7% higher than the exported crops (tons) in 2000. The share of Australian livestock production that is exported increased from 13% to 44% between 1961 and 2000. By 2013 only around one-third of the livestock production was exported. Similarly, the tonnage of livestock exports decreased around 29% from 2000 to 2013. Historical export trends suggest that achievement of the Current Trends and Sustainable Pathways export targets would require significant improvements in agricultural productivity.





FOOD Average dietary composition (daily kcal per commodity group or % of intake per commodity group)	
Current Trends Pathway	**Sustainable Pathway**
No change in Australian diets relative to 2000-2010.	Gradual adoption of healthy domestic diets. Relative consumption/cap: decreases 6% for red and monogastric meat and increases 8% for cereals and 11% for pulses by 2050. A gradual transition towards healthy diets is modeled based on recommendations from the Eat-*Lancet* Commission on healthy diets from sustainable food systems (Willett et al., 2019).
The diet scenarios consider the structure of the domestic population (age and sex composition) to set an average calorie/cap intake target to 2050. We used as a baseline 2500 kcal/cap, which is the average minimum daily energy activity for 20 to 24-year-old people with intermediate activity. Such baseline is consistent with the EAT-Lancet recommendation. The Australian diets scenario in the FABLE calculator is based on adjusted EAT-Lancet scenarios. The initial diet target by product group was multiplied by the ratio between the average national minimum dietary energy requirement and the total kilocalories in the EAT-Lancet diet to approximate a healthy diet specific to the Australian population.	

FOOD Share of food consumption which is wasted at household level (%)	
No change to household food waste levels relative to 2010 values. This scenario was selected to estimate potential implications of the continuation of food waste levels at current levels.	Reduction of household food waste of 20% by 2050 relative to 2010 levels. Existing investment and government/research focus on improved logistics to lift the value of Australian exports could have a knock-on effect on household waste resulting from produce arriving in better condition to market and having a longer shelf life. This is compounded with increased household awareness around food waste and healthy national diets (e.g. EAT-Lancet and Australian Dietary Guidelines recommending a larger share of wholegrain and wholemeal foods than under current diets). The Australian Government has set a target to halve food waste by 2030. Some of the actions to achieve such target include: negotiating voluntary waste reduction commitments for the food industry; redistributing food to the food rescue sector; educational campaigns; and research and technological improvements (DAWE, 2020). Here we set 20% reduction in household waste, which in addition to the 30% reduction in post-harvest losses by 2050 modeled under the Sustainable Pathway, is close to a delayed implementation of the National Farmers Federation 2030 target (National Farmers Federation, 2020).

Australia

BIOFUELS Targets on biofuel and/or other bioenergy use

Current Trends Pathway	Sustainable Pathway
Biofuel demand continues at 2010 levels.	

Biofuels in the model introduce additional demand for crops and vegetable oils based on projections from the OECD-FAO Agricultural Outlook 2019. This outlook only makes projections until 2028. Biofuel production also leads to some CO2 savings compared to fossil fuel use which are added to the total GHG accounting. Substitution of animal feed by biofuel by-products is not included in the analysis.

According to the USDA Foreign Agricultural Service data (USDA Foreign Agricultural Service, 2018), the biofuel industry in Australia is small with around 290 million liters of production from 2017 to 2019 which represents a 27.5% decline of its production peak in 2014. Around 86% of the domestic biofuel production is comprised of fuel ethanol and the rest by biodiesel. Fuel ethanol in Australia is manufactured from wheat waste, sorghum grain and sugar, and accounts for around 2% of the total petrol sales in Australia. Its production has been relatively stable due to regulatory incentives in New South Wales, and Queensland. Biodiesel production has reduced due to high production costs and low oil prices. Lack of country-level biofuel support programs, low international oil prices and high feedstock prices limit the expansion of biofuels production for the foreseeable future. If second-generation biofuels (e.g. algae-based fuels) become commercially viable, the assumption of no changes in the domestic production capacity and demand for biofuels may need to be revised.

CLIMATE CHANGE Crop model and climate change scenario

Current Trends Pathway	Sustainable Pathway
RCP 6.0; GCM:HadGEM2-ES; crop model: GEPIC	RCP 2.6; GCM: HadGEM2-ES; crop model: GEPIC

Climate change impacts on crop yields, water withdrawal and fertilizer use, were estimated through the GIS-based Environmental Policy Integrated Climate (GEPIC) model (Liu et al., 2007). Climate change scenarios from the corresponding to RCP 6.0 and RCP 2.6 were agreed by the FABLE consortium as representative of global Current Trends and Sustainable Pathways. The Hadley Centre Global Environmental Model, version 2 (HadGEM2-ES), was used to estimate the effects of historical and projected greenhouse gas emissions associated with the Representative Concentration Pathways (RCPs) 6.0 and 2.6 (Caesar et al., 2013). No fertilization effects were considered in the analysis.

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

g – gram

GHG – greenhouse gas

ha – hectare

kcal – kilocalories

kg – kilogram

km^2 – square kilometer

km^3 – cubic kilometers

m – meter

Mha – million hectares

ML - megalitres

Mm^3 – million cubic meters

Mt – million tonnes

t – tonne

TLU –Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – tonne per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- tonne per TLU, kilogram per TLU, tonne per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year

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