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Agriculture's carbon neutral challenge: The case of Western Australia*

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Agriculture is being encouraged to become carbon neutral, and agricultural land is being touted as a source of carbon sequestration. Yet making agricultural regions locally carbon neutral will involve an economic cost, with existing patterns of greenhouse gas emissions and spatial costs of abatement affecting that cost of achieving regional carbon neutrality. This study examines the economic cost of locally achieving carbon neutrality, using the illustration of Western Australia's agricultural region. The cost to the region of achieving carbon neutrality via reforestation is estimated, as is the spatial allocation of farmland for sequestration. Social and political pressures that likely constrain how much farmland can be reforested are explicitly considered. Findings are subject to a sensitivity analysis and several caveats. The annual cost of regional carbon neutrality via proscribed regional reforestation, under current carbon offset prices, is estimated to range from AUD216 million to AUD250 million (i.e. under 3 per cent of the region's gross value of agricultural production) which might suggest the challenge to be carbon neutral is within commercial reach. However, without other financial incentives, it likely involves farm business profits being reduced by around 15 per cent.

Key words: agriculture, greenhouse gas emissions, reforestation, sequestration, spatial analysis.

1. Introduction

Within and outside of agriculture, support for carbon neutrality is growing. In Australia, key agricultural organisations have announced plans and commitments to achieve carbon neutrality (Beattie, 2020; GrainGrowers, 2020; MLA, 2019; NFF, 2020) and various governments, including Victoria, South Australia, Tasmania and the Australian Capital Territory, have passed legislation to meet a target of net zero emissions by 2050 (or earlier), often including targets of greater reliance on renewable energy (Button, 2020). Similarly, to lessen greenhouse gas emissions, Australia's federal government has signed two international climate agreements, the Kyoto Protocol and the Paris Agreement, that commit Australia to reduce, respectively, its

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greenhouse gas emissions to 5 per cent below 2000 levels by 2020 and to 26–28 per cent below 2005 levels by 2030.

How easily and affordably agricultural businesses, industries or regions might achieve carbon neutrality depends on many factors, including path dependence as the past can influence both current emissions and future emission trajectories. Australia's agricultural history is dominated by grazing and cropping industries whose production technologies and emissions have altered, but often not rapidly. Beef, sheep, wool and grain production still dominate agricultural land use in Australia. In 2019, Australian agriculture produced 70.6 Mt of CO_2-e or 13 per cent of the nation's emissions (DISER, 2020a). Methane emissions, mostly from cattle, have persistently been the dominant source of agricultural emissions.

To reduce agricultural emissions would require some combination of lowering emissions at source (e.g. DAFF, 2012), or using agricultural lands for sequestration via improved levels of soil carbon in some situations (Lam et al. 2013; Sanderman et al. 2010). It could also be achieved either via agroforestry (George et al. 2012; Reeson et al. 2015; Schoeneberger, 2009) or re-vegetation (Rooney & Paul, 2017), as well as through avoiding land clearing (CIE, 2015).

This study focuses on how agricultural carbon neutrality might be achieved via reforestation, where the challenge is to cost-effectively provide sequestration services that reduce net emissions from agricultural activities to the point of carbon neutrality. The agricultural region of Western Australia (WA) is used as a case study. The region generates almost 40 per cent of Australia's wheat, barley and canola production and supports 20 per cent of the nation's sheep flock.

The contribution of this study is that it identifies how agricultural carbon neutrality can be achieved via reforestation, in a least-cost way in a key farming region of Australia, whilst uniquely allowing for likely social and political restrictions on reforestation of farmland. Such restrictions are almost always overlooked in sequestration studies, yet this current study's novel contribution is that it explicitly considers these practical limitations. The sub-regions most suited to cost-effective reforestation that enable the entire region to achieve agricultural carbon neutrality are also identified. In addition, the study discusses how responses from consumers and governments can help lower the cost impacts on farm businesses of reforestation. This study uses the most recent emission factors, updated in 2020, to display the spatial and temporal changes in agricultural emissions in the study region that form an important backdrop to this study.

The following section outlines emissions accounting and the derivation of the marginal cost of abatement in the study region. The section also incorporates sub-sections that give technical background on agriculture as both a source and sink (Flugge & Abadi, 2006; Garnaut, 2008) of greenhouse gas emissions, and a linear programming (LP) model of how to achieve carbon neutrality at least cost is described. This is followed by the presentation and discussion of results.

The concluding section offers discussion on the commercial feasibility of ensuring that agricultural production in the region can be carbon neutral through reliance on emissions abatement based on reforestation.

2. Method

Before outlining the details of the study's method, the following two subsections provide some technical background on agriculture as a source of emissions and reforestation as a source of emissions abatement.

2.1 Agricultural sources of greenhouse gas emissions

Greenhouse gases are released when biomass decays or is consumed or burnt (National Greenhouse Gas Inventory, 2007). Agricultural practices have increased these processes through the introduction of cropping and livestock systems. The primary greenhouse gases produced by agriculture are methane (CH_4) and nitrous oxide (N_2O) (IPCC, 2007). Methane and nitrous oxide have a greater Global Warming Potential (GWP) than carbon dioxide with their GWP values that underpin the terms of the Paris Agreement, being 28 and 265, respectively (DISER, 2020a).

Agriculture is responsible for 85 per cent of Australia's total nitrous oxide emissions primarily due to the application of nitrogenous fertilisers, cultivation of nitrogen-fixing crops and pastures, and tillage of agricultural soils (Australian Greenhouse Office, 2007; Department of Climate Change, 2008b). Agriculture is also responsible for 60 per cent of total methane emissions (Australian Greenhouse Office, 2007). Methane is released from the process of enteric fermentation in the digestive system of livestock, particularly in ruminants. In anaerobic conditions, methane can also be produced from manure and this is particularly associated with intensive livestock industries. Nitrous oxide can be released from manure and urine on soil, but emissions are only significant in high rainfall areas (National Greenhouse Gas Inventory, 2007).

A growing source of agricultural emissions is the soil amelioration practice of liming to increase soil pH on acidic soils and thereby improve plant growth. Incorporation of lime into acidic soils causes a chemical reaction that produces CO_2. In some states, particularly in WA, there are large areas of acidic or acidifying soils that benefit from periodic applications of lime. Umbers (2017) notes that since the mid-2000s the percentage of the crop area limed in most grain-growing regions of Australia has increased from approximately 5 per cent to around 25 per cent in 2016. However, the rate of lime applied has remained fairly stable at under 2 tonnes per hectare. A further growing source of emissions is due to farmers opting to run more crop dominant farming systems that involve applying more urea fertiliser to support higher-yielding varieties and a greater role of canola in cropping programmes with canola requiring higher rates of application of urea. A corollary is a diminished role of leguminous pastures in farming systems that encourages farmers to replace their biological nitrogen with nitrogen from fertilisers.

2.2 Reforestation as a carbon sink

Agriculture can reduce or offset its greenhouse gas emissions through reforestation or agroforestry that sequester carbon dioxide (Doran-Browne et al. 2016; Flugge & Abadi, 2006; Kragt et al. 2012; Land & Water Australia, 2007). Articles 3.3 and 3.4 of the Australian ratified Kyoto Protocol allow for emission offsets through the sequestration of carbon. Article 3.3 covers reforestation and afforestation activities occurring after 1990, subject to the following conditions (DAFWA, 2003):

- Land was cleared prior to 1990.
- Trees at a minimum height of 2 metres.
- Forest crown cover of at least 20 per cent.
- Forest area greater than 1 hectare.
- Forest established by direct human methods.

Reforestation and plantation-based sequestration activity under Article 3.3 are supported by the Emissions Reduction Fund (ERF). The Plantation Forestry Methodology Determination (also known as the ERF Plantation Forestry Method) covers the establishment of a new plantation forest, conversion of a short-rotation plantation to a long-rotation plantation, or maintenance of a pre-existing plantation forest that meets the eligibility requirements of the method. Projects approved by the Clean Energy Regulator generate Australian Carbon Credit Units (ACCUs) where each ACCU represents a tonne of carbon dioxide equivalent net abatement (through either emissions reductions or carbon sequestration) achieved by the eligible project. A new additional step in the project approval process is that the federal minister for agriculture, water and the environment may also assess if a proposed project could lead to an undesirable impact on agricultural production in the region in which the project would be located.

The ERF Plantation Forestry Method complements agroforestry activity permissible under the Carbon Farming Initiative (CFI). The CFI was a voluntary carbon abatement scheme that ran between September 2011 and December 2014 after which it was integrated with the ERF such that an existing CFI project automatically became an Emissions Reduction Fund project. The regulatory burden for forestry sector participation in the ERF was eased in 2020, whilst recognising the need to ensure ERF forestry projects would not pose a cumulative adverse risk for water availability (DAWE, 2020).

Several requirements must be satisfied before a forestry or reforestation project can be declared an 'eligible offsets project' including, among other things, that the project must comply with an approved methodology and the project proponent must report to the Regulator about the conduct of the project and the abatement achieved, with certain reports being prepared by a registered greenhouse and energy auditor. Importantly, the permanence rules require that the carbon stocks in sequestration projects be retained for 100 years, although the ERF has introduced an optional permanence period of 25 years. However, a project proponent using the 25-year period will receive 20 per cent fewer ACCUs (CIE, 2015).

Harper et al. (2007) identified significant opportunities for carbon sequestration in WA's agricultural zone through the reforestation of farmland. They suggested the greatest potential for carbon storage by trees was in higher rainfall areas. However, Shaikh et al. (2007) argued that carbon sinks on marginal agricultural land could also provide significant emission offsets. In WA, land in higher rainfall areas tends to be more productive for agriculture and forestry than land in lower rainfall regions. Hence, agricultural land in high rainfall zones has a greater opportunity cost than land in low rainfall regions. Van Kooten et al. (2004) found that including the opportunity cost of land caused the average costs of forest carbon sinks to rise significantly. Similarly, Richards and Stokes (2004) found differences between studies that have included land opportunity costs and those that have not. More recently, Mitchell et al. (2012) and Polglase et al. (2013) have reviewed the prospects for carbon forestry in Australia. Polglase et al. (2013) applied plausible assumptions for cost of establishment and a commercial discount rate of 10 per cent, and found a carbon price of at least AUD40 per tonne of CO_2-e was required before forestry investments were commercially attractive. George et al. (2012) examined agroforestry in the agricultural region of WA and concluded that agroforestry's future viability lay with it being rewarded for multiple outcomes: carbon sequestration, biofuels, biodiversity restoration and water catchment regeneration. Using farmland for carbon sequestration was not commercially attractive at the then current carbon prices. Reeson et al. (2015) examined the role of agroforestry for a case study farm in northern Tasmania, highlighting how flexible management of agricultural enterprises generated additional benefits relative to agroforestry.

2.3 Emissions accounting

In this study, greenhouse gas emissions were calculated using emissions factors and equations from the National Greenhouse Accounts, including equation 3G_1 (DISER, 2020b) for emissions from liming and equation 3H_1 for emissions from applications of urea. Shire-level data on livestock numbers and type, crop and pasture production and quantity of nitrogenous fertiliser applied were obtained from the Australian Bureau of Statistics (ABS) for the 1990, 1995, 2000, 2005, 2010 and 2015 census years for eighty statistical local areas (shires) in WA's agricultural zone. Some gaps in census data were filled using farm management consultancy data.

The combined data sets were used to calculate emission categories including methane emissions from enteric fermentation and manure, nitrous oxide emissions from direct soil nitrogen (nitrogenous fertiliser application and nitrogen-fixing crops and pastures), indirect nitrogen leaching and from manure and urine on soil, emissions from liming of soils and nitrous oxide emissions from urea applications. Methane and nitrous oxide emissions were converted into carbon dioxide equivalents (CO_2-e) using Global Warming Potentials (GWP) of 28 and 265, respectively, as applied by the Australian Government from 2020/21 onwards, in accordance with the terms of the Paris Agreement. The only emissions not included in this study are emissions from residue burning. These emissions have reduced substantially over the last 25 years due to the now common practice of retention and incorporation of stubbles into soil profiles (Duck et al. 2006; Umbers, 2017). Umbers (2017) reports an Australia-wide farm survey in 2016 that reveals less than 10 per cent of farmers' total crop area was burned. Unfortunately, there are no consistent farm survey data recording the practice of stubble burning over the last 25 years at a shire level in WA. The DISER (2020c) estimates of emissions from stubble burning in WA reveal they are currently less than 0.5 per cent of total emissions from the WA agricultural sector. Fuel consumption by agricultural practices is not included, as this is accounted for under the transport sector in the National Greenhouse Accounts.

Greenhouse gas emissions were calculated on a shire basis for the agricultural zone of WA for the years 1990, 1995, 2000, 2005, 2010 and 2015. Plus, based on ABS divisional intercensual and industry data, available after 2015, emissions from agricultural shires in 2020 were estimated. The reader is referred to the Australian Methodology for the Estimation of Greenhouse Gas Emissions and Sinks 2006: Agriculture (National Greenhouse Gas Inventory, 2007) and the DISER (2020b) National Inventory Report 2018 for further details of the accounting methods. Note that the revised national emissions factor of 0.3 was used for NOx emissions associated with agricultural soils, rather than the international factor of unity. Shire-level emissions were mapped using GIS software to determine spatial and temporal patterns.

Although the estimation of emissions in this study applies a historically consistent methodology, it is acknowledged that other ways of measuring emissions can generate quite different estimates (Thamo et al. 2013; Young et al. 2016) and emission factors that underpin Australia's National Greenhouse Accounts have been subject to change and so affect the levels and relative importance of different categories of emissions (DISER, 2020b). The emission data sets that underpin this analysis are available as an online accompaniment to this article.

2.4 Marginal cost of abatement estimation

The reforestation marginal cost of abatement (see later Figure 6) drew on several data sets and calculations involving shires' farmland values, plantation establishment and maintenance costs (Table 1), and transaction costs to establish the carbon offsets.

The average value of cleared farmland in each shire was taken from Landgate (2012) and Rural Bank (2019 & 2020) farmland valuations. Missing values for some shires in the Rural Bank data set were filled by extrapolating from land value growth rates contained in the more detailed Landgate data set that tracked annual farmland values in every shire from 1970 to 2011. The eighty shires that comprise the agricultural region have farming as their dominant land use. Hence, at least historically, the value of farmland is mostly a function of its value of use for agriculture rather than for forestry. However, if carbon prices increase substantially to reward reforestation, then land values will increase commensurately. For example, the original modelling for the now defunct Carbon Pollution Reduction Scheme (Commonwealth Government, 2008b) indicated that although there was uncertainty about the worth of emission offsets in coming years, the carbon price was nonetheless assumed to increase in real terms from starting prices in the range 9USD/t to 47USD/t of CO_2-e. Similarly, in their analysis of Australia's mooted emissions trading scheme, Keogh and Thompson (2008) assumed a carbon price of AUD30 per tonne in 2010 increasing to AUD110 per tonne by 2030. More recently, Reeson et al. (2015) considered carbon prices in the range of AUD25 to AUD50/t of CO_2-e, yet at the tenth Emissions Reduction Fund (ERF) auction in 2020, 1.7 million ACCUs were purchased at an average price of only AUD16.14/t of CO_2-e (CER, 2020). The average price in the preceding auction in 2019 was also relatively low, being only AUD14.17/t of CO_2-e (CER, 2019).

In this study, we assume farmland values will continue to be most influenced by the profitable use of the land for farming and so historical trends in real farmland prices are a useful guide for future trends. Specifically, we assume that real prices of farmland will increase by 1 per cent per annum and that a 4 per cent real opportunity cost of farmland will apply to its switching into reforestation. Obviously, if a market consensus formed that the worth of

Table 1 Reforestation costs in 2020

Activity	Cost (AUD'000)
Accreditation and registration†	3
Legal fees/advice†	2
Initial verification report†	1.7
Multi-species tree planting	2.5 per hectare
Annual maintenance (fire-breaks, weed control, etc.)	0.035 per hectare
Annual reporting and auditing†	1.2

†These fixed cost components were converted into per hectare costs by assuming each plantation investment was based on unit plantations of 250 hectares.

emission offsets would strongly increase in real terms, exceeding returns from future agriculture, and assuming no government regulation prevented reforestation of farmland, then competition for farmland would lead to greater land price appreciation. In such a case, the land values that underpin this analysis would no longer be relevant, as those farmland prices mostly reflect the worth of that land for agricultural purposes. Thamo et al. (2017) reinforce this point by revealing that most sequestration studies fail to be explicit in their assumptions about the future carbon price. In our particular case, we assume that the carbon price trajectory will be such that the value of agricultural land will remain principally influenced by the value of its use for agriculture. As such, we combine land values with a 4 per cent real opportunity cost of farmland to reflect land lease costs. Discussions with farm management consultants who operate in the study region revealed that the current nominal annual lease price of farmland is around 6 per cent of the value of the farm property. Assuming, an underlying annual inflation rate of 2 per cent, a 4 per cent real opportunity cost of farmland equates to about a 6 per cent nominal annual lease price. However, if farmland is reforested for carbon sequestration, it is largely an irreversible investment and as such many farmers may require an even higher premium to trigger such a change in land use. The assumption that the value of agricultural land will remain principally influenced by its value for agriculture means that the initial real carbon price that underpins subsequent analyses in this paper is AUD16.5 per ACCU. In other words, the marginal cost of abatement (see later Figure 6) in the agricultural region lies above the currently observed market price for ACCUs.

Plantation establishment and maintenance values were drawn from studies of agroforestry in the region (Abadi et al. 2006; CIE, 2015; Department of Agriculture & Food, 2003; Polglase et al. 2008; Sudmeyer et al. 2014), with all costs expressed in constant 2020 AUD terms and assuming reforestation plot sizes were 250 hectares. The plantation establishment costs included planning, legal costs, site preparation, weed and pest control, seedling purchase, machine planting, initial growth monitoring and on-going reporting (Table 1). Planning, administrative and participation costs associated with ensuring any plantation investment accords with an eligible offsets project as defined by the CFI or ERF Plantation Forestry Method were included. These transaction costs are known to play a large role in determining the cost-effectiveness of a particular abatement strategy (Ancev, 2011; Cacho & Lipper, 2007).

Additional edge-effect costs associated with tree plantations were not considered. In addition, harvest costs were not included in this study as trees were assumed to be unharvested in accordance with the Australian adopted Kyoto accounting standards, which treats harvest as a release of all stored carbon (Australian Greenhouse Office, 2006). All costs, including annual lease costs, were expressed in constant 2020 AUD over a 100-year horizon to reflect the statutory requirement for permanence, whereby newly established forests need to remain in place for 100 years to qualify for their full complement of

ACCUs (CIE, 2015). The cost streams were then expressed in present value terms.

Sequestration rates can be estimated in various ways, such as via FullCam generic modelling, or site or project-specific FullCam modelling, or by field sampling inventories of stem diameters and applications of allometric equations (Rooney & Paul, 2017) and earlier until 2018, through use of the CFI Reforestation Modelling Tool (DEE, 2014). FullCam (Full Carbon Accounting Model) is a calculation tool for modelling Australia's greenhouse gas emissions from the land sector as reported in Australia's national greenhouse gas accounts. Polglase et al. (2013) comment on how difficult it is to generate reasonable spatial predictions of sequestration on cleared land. For the study region, we drew on Forest Product Commission shire-level data and the expert opinion of Professor Harper at Murdoch University on sequestration rates (George et al. 2012; Harper et al. 2007; Harper et al. 2017) in the region's shires, assuming tree growth patterns were sigmoidal and maximum sequestration occurred at 40 years (Yin et al. 2003). Sequestration rates were adjusted downwards to account for the observed decline in rainfall in many parts of the study region since the mid-1970s (DPIRD, 2020) in acknowledgement of Simioni et al.'s (2008) and Thamo et al.'s (2019) finding that historically observed sequestration rates likely overstate future tree growth rates due to current and projected adverse climate change in the region (Stephens, 2017). Across the 100 years of the commitment to sequestration, the annualised carbon storage growth rates that qualify for ACCUs ranged from 1.8 tonnes of CO_2-e per hectare of ACCUs to 11.2 tonnes of CO_2-e per hectare of ACCUs, consistent with the rates estimated by Polglase et al. (2013) across the study region. An accompanying online data file outlines the shire-level data and assumptions that underpin the estimation of sequestration rates and costs.

The sequestration data sets were combined firstly with data sets of the area of farmland in each shire, and consequently with the financial data sets to determine the marginal cost of generating ACCUs per shire, as shown in Figure 6. Each data point in Figure 6 represents the trigger price at which farmland in a particular shire is reforested to generate an average annual quantity of ACCUs.

2.5 Modelling the cost of carbon neutrality

Drawing on the shire data that underpins Figure 6 it is possible to examine the cost and feasibility of the entire region being able to fully or partially offset its agricultural emissions. Offsetting the region's agricultural emissions within the same region is one way of internalising what would otherwise be an externality. Completely offsetting the region's agricultural emissions would result in carbon neutrality.

Where sequestration will occur in the study region, if different amounts of abatement are sought up to the point of carbon neutrality, can be couched as a steady-state linear programming (LP) land allocation problem. Its objective is the minimisation of the cost of required abatement. This objective is subject to a range of constraints including social or political constraints on how much farmland in each shire can be switched into reforestation. These likely political or social restrictions are represented by proportion p of each shire's land being made available for sequestration activity, with proportion q of the region's agricultural emissions needing to be offset by sequestration activity. The LP problem can be stated mathematically as:

$$Min \sum_{i=1}^{n} l_i C_i \tag{1}$$

subject to:

$$(l_i + a_i) = T_i \, \text{for each shire} \, i = 1, 2, \ldots, n \tag{2}$$

$$l_i \leq pT_i \, \text{for each shire} \, i = 1, 2, \ldots, n \tag{3}$$

$$\sum_{i=1}^{n} l_i S_i \leq \sum_{i=1}^{n} a_i E_i \tag{4}$$

$$\sum_{i=1}^{n} l_i S_i = q \sum_{i=1}^{n} a_i E_i \tag{5}$$

$$l_i \geq 0.$$

$$S_i \geq 0.$$

$$E_i \geq 0.$$

Where l_i is the land (hectares) allocated for sequestration in shire i. a_i is the land (hectares) allocated for agriculture in shire i. C_i is the annual cost (in 2020 AUD) of sequestering a tonne of CO_2-e per hectare in shire i. T_i is the total area of land (hectares) available for agriculture and sequestration in shire *i*. *p* is the proportion of land available for agriculture and sequestration in shire *i* that is legally able to be devoted to sequestration activity. *q* is the proportion of total annual emissions from agriculture that must be offset annually by sequestration activity. S_i is the tonnes of CO_2-e sequestered annually per hectare on land allocated for sequestration in shire *i*. E_i is the emissions (tonnes of CO_2-e per hectare) generated annually on agricultural land in shire *i*. *n* is the total number of shires in the study region ($n = 80$).

The constraint equation 2 describes how the farmland in each shire must be allocated either to agriculture and/or reforestation. Equation 3 is a political or social constraint that indicates that up to a proportion *p* of the land available for farming and reforestation in each shire, can be reforested. Equation 4 specifies that the region's annual sequestration should not exceed the region's annual agricultural emissions. Equation 5 modifies equation 4 inasmuch as it allows the pathway to carbon neutrality to be examined whereby only a portion of the region's annual agricultural emissions are abated via reforestation. The other constraint equations are non-negativity conditions that typify most LP problems.

Reforestation of farmland is often associated with social conflict over its perceived detrimental economic and social impacts (Schirmer, 2007). Williams (2008) surveyed community attitudes to wood plantations in the study region and found that respondents valued agricultural land use higher than plantation forestry. Moreover, many people believed plantations offered benefits primarily to companies and a few individuals and created only limited regional employment and economic benefits. These views were later cemented following the collapse of many forestry managed investment schemes that operated in the study region (Ferguson, 2014). Hence, given those views and the history of failure of plantation investment schemes in the study region, it is highly unlikely that any state or local government would support wholesale reforestation of farmland in the region's shires. More likely is that a proportion of farmland in any shire will be permitted to be switched from agriculture into forestry (hence the need for *p* in the above LP model). This is yet another example of path dependency whereby the regional history of land use is not easy to rapidly alter. Convincing regional communities of the desirability of replacing traditional agricultural activity with permanent multi-species tree plantations is a political and social challenge.

3. Results and discussion

3.1 Temporal trends in the region's emissions

As stated in the introduction, path dependency issues can affect the magnitude of the carbon-neutral challenge for an agricultural business, industry or region. The temporal trends in the region's emissions and the spatial distribution of those emissions form the backdrop for assessing the current cost of the region's economic challenge to be carbon neutral. In the case of the agricultural region of Western Australia, its greenhouse gas emissions have been falling; from 10.4 Mt in 1990 to 7.4 Mt of CO_2-e in 2015 (Figure 1) and are estimated to remain near 2015 levels in 2020. Greenhouse gas emissions shown in Figure 1 for all years, apart from 2020, were based on shire-level data sets, principally derived from ABS agricultural censuses. The projected estimates for 2020, however, were based on individual shire trajectories over the period 1990 to 2015, supplemented with key annual aggregates since 2015 such as the size of WA's cattle and sheep population, state-wide agricultural use of lime and urea and ABS sub-divisional survey data.

Enteric fermentation and direct soil nitrogen remain the most important sources of emissions in the study region. The reduction in total emissions was principally due to the decrease in enteric emissions, which fell by 40 per cent, from 7.8 Mt of CO_2-e in 1990 to 4.7 Mt of CO_2-e in 2015. Enteric emissions in 1990 were responsible for 75 per cent of all emissions; but by 2015, this figure had fallen to 63 per cent. This change was mostly caused by declining sheep numbers and reflected the move into more intensive cropping systems in WA agriculture (Kingwell & Pannell, 2005; Thamo et al. 2019).

Liming, as a contributor to total agricultural emissions, increased its share from 0.3 per cent in 1990 to 10 per cent in 2015. Similarly, emissions from urea applications increased their share from 1 per cent in 1990 to almost 6 per cent in 2015. Hence, the marked dominance of livestock enterprises, as the

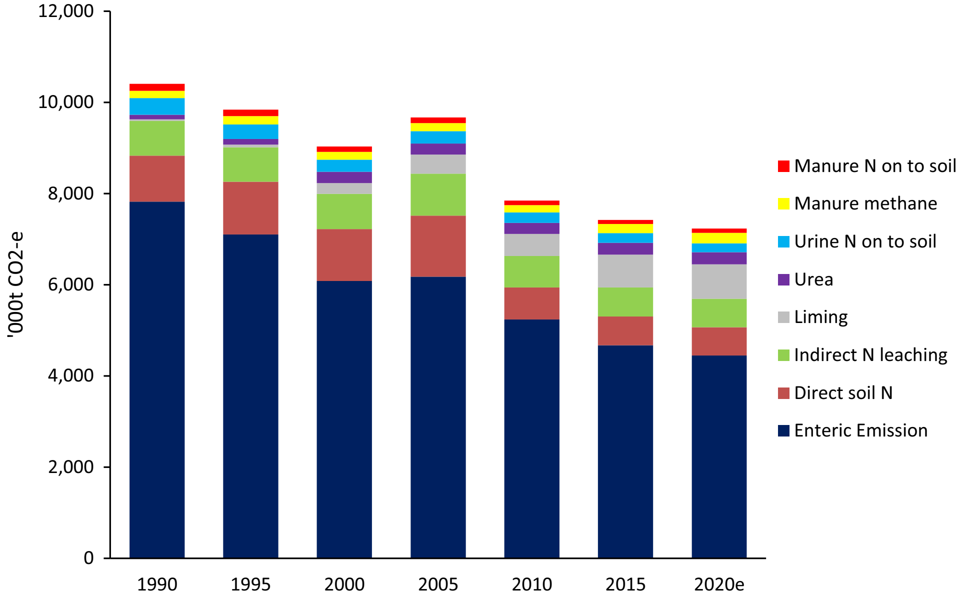

Figure 1 Western Australia's agricultural region greenhouse gas emissions by source: 1990–2020e. [Colour figure can be viewed at wileyonlinelibrary.com]

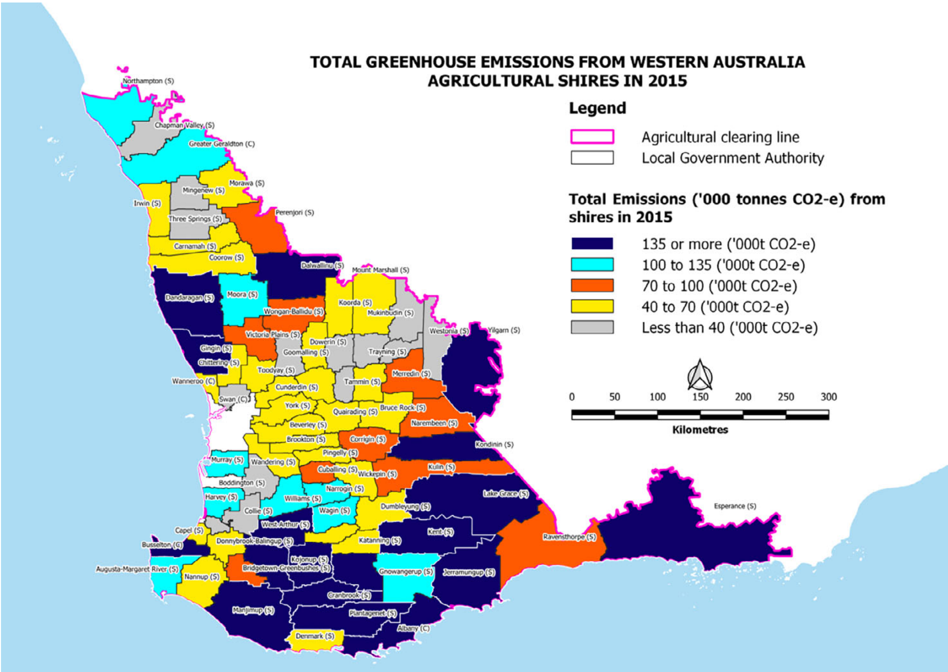

Figure 2 Shire emissions in 2015. [Colour figure can be viewed at wileyonlinelibrary.com]

principal source of agricultural emissions, so evident in the 1990s, is now changing with emissions from cropping growing strongly.

Note the region shown in Figure 2 is the source of the bulk of WA's agricultural emissions. Other regions in WA are minor sources of additional emissions via pastoral cattle and irrigated horticultural production (e.g. Ord River irrigation district). By illustration, in 2005 WA's agricultural emissions were 10.8 Mt of CO2-e (DISER, 2020c), whereas emissions from the 80 shires in the south-west agricultural region (i.e. Figure 2) were 9.7 Mt of CO2-e.

In the years 2000 and 2010, there was widespread drought, leading to distinct falls in agricultural emissions. Grain and pasture production were poor, leading to destocking and reduced emissions from both cropping and livestock. In contrast, 2005 was an above average season (Duck et al. 2006) with ample early rains that boosted soil moisture reserves (Kingwell et al. 2013) and encouraged farmers to apply additional nitrogenous fertilisers and retain livestock due to strong early growth in pastures. The result was increased emissions from cropping and livestock. Intercensus data after 2015 suggest that estimated emissions in 2020 will be slightly less than levels recorded in 2015.

3.2 Spatial patterns of emissions within the region

Spatial variability characterises the study region's agricultural emissions. The highest emitting shires are predominately in the south, where livestock dominant and higher crop input farming systems operate and where some shires have a large area (e.g. Esperance, Lake Grace) (Figure 2). The lowest emitting shires are mainly in the central wheat belt, where the sheep population has been greatly reduced and where shires are small in area (e.g. Nungarin, Tammin).

By 2015, 89 per cent of shires had reduced their emissions from 1990 levels (Figure 3). The exceptions were firstly, in the few shires that increased their emphasis on milk and cattle production and so had increased enteric emissions (Figure 4). Secondly, some shires (e.g. Cuballing, Narrogin) intensified jointly their crop and livestock production and so slightly increased their emissions. Thirdly, some crop dominant shires along the low rainfall eastern edge of the grainbelt increased their emissions mostly due to the combination of increased applications of urea in favourable years for grain production, increased emissions from greater use of liming, particularly over the last decade, and retained or slightly increased sheep or cattle numbers. Importantly, many southern region shires (e.g. Esperance, Ravensthorpe and Plantagenet) that were major sources of emissions, substantially reduced their emissions from 1990 levels. Often the principal cause of the emissions reduction was a swing away from sheep production towards grain production, as evidenced by the decline in enteric emissions (Figure 4).

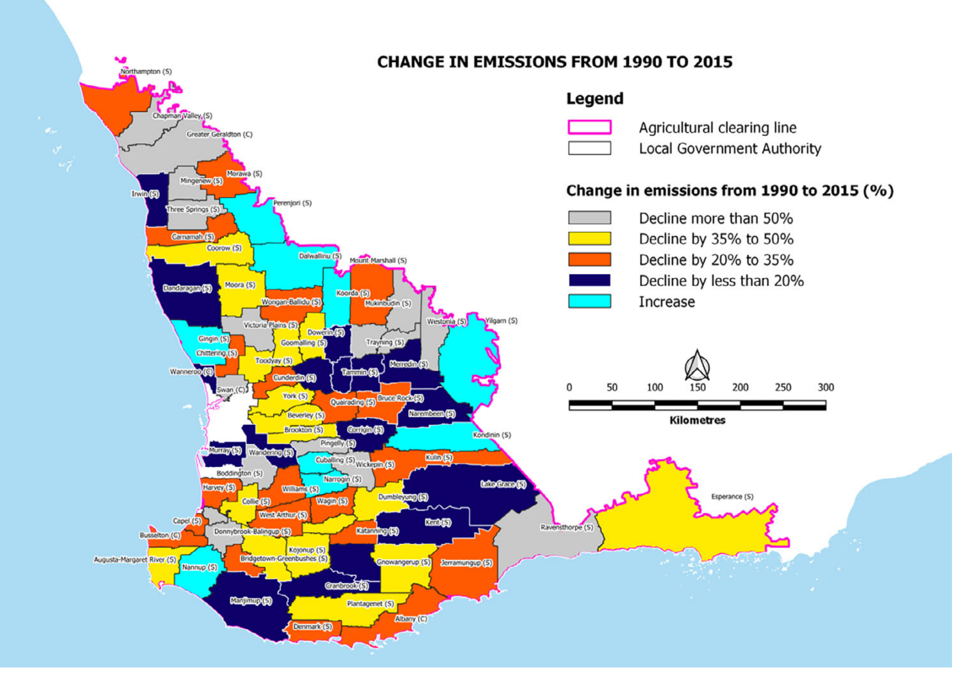

Figure 3 Change in shire emissions: 1990–2015 (%). [Colour figure can be viewed at wileyonlinelibrary.com]

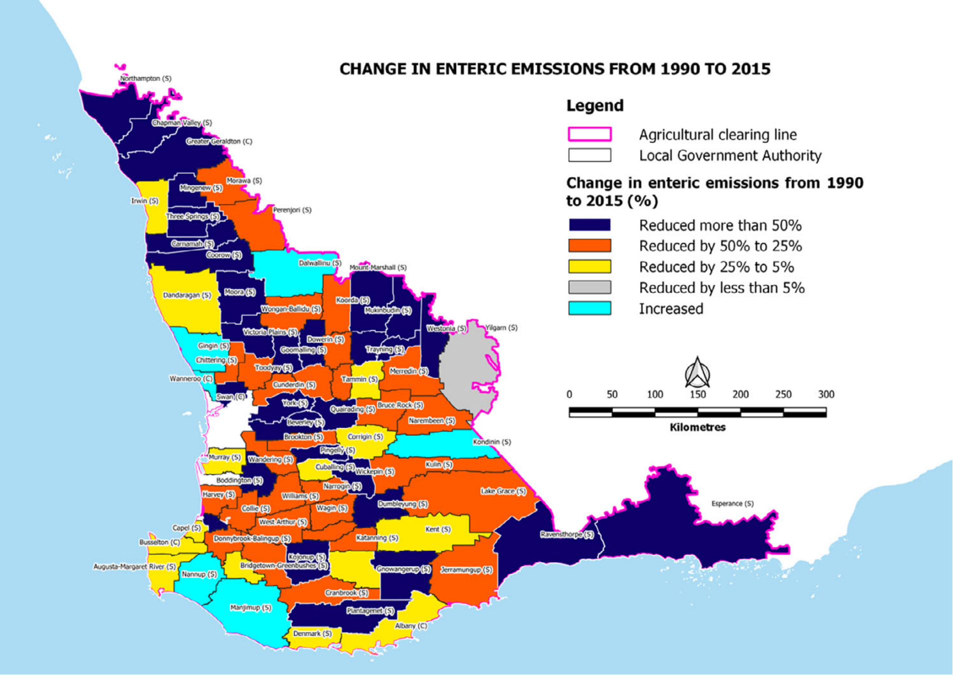

Figure 4 Changes in shire enteric emissions: 1990–2015 (%). [Colour figure can be viewed at wileyonlinelibrary.com]

The swing away from sheep production since 1990 triggered by the collapse of the Reserve Price Scheme for wool in 1991 (Bardsley, 1994) and aided by subsequent productivity gain in cropping (Hughes & Lawson, 2017) saw large declines in sheep populations in the northern and central parts of the study region. Most shires generated decreases in emissions due to falls in enteric emissions that exceeded the rise in cropping-related emissions such as increased applications of lime and urea. The sheep population in WA declined from 36.5 million in 1990 to 13.9 million in 2015, a 62 per cent reduction.

Examination of the shire data that underpins Figure 1 reveals that 76 per cent of all shires in the study region will qualify as fulfilling Kyoto Protocol obligations to reduce greenhouse gas emissions to 5 per cent below 2000 levels by 2020. In addition, 56 per cent of shires are currently on track to satisfy Paris Agreement targets to reduce emissions 26–28 per cent below 2005 levels by 2030, having already reduced their emissions by over 28 per cent below 2005 levels by 2020.

Future agricultural emissions in the study region will mostly depend on changes to cattle and sheep populations. Since 2015, the sheep population in WA has stabilised whilst the WA cattle population has continued to decline from 2.24 million head in 2015 to 1.88 million in 2019. However, high prices for sheepmeat and beef in recent years, plus planned major production investments in beef cattle production could see an increase in cattle and sheep numbers and so enteric emissions towards 2030 may increase. Hence, the 56 per cent of shires currently on track to satisfy Paris Agreement targets may not all stay their course, and therefore, some would need to access either emission offsets or emission-reducing innovations to satisfy the Paris Agreement target.

Consideration of the spatial pattern of emissions highlights those parts of the region that are the main sources of emissions and therefore identifies those businesses or industries liable to face the greatest challenges to achieve carbon neutrality.

3.3 The region's marginal cost of abatement

Besides being a source of emissions, the study region, through investment in reforestation, is also a potential source of abatement. Eligible offset projects as defined by the CFI or ERF Plantation Forestry Method can provide farmers (and others) with the opportunity to use reforestation to reduce net emissions by creating ACCUs. However, for the study region, there is limited current information on the spatial marginal cost of creating ACCUs through reforestation.

The *Method* section of this paper outlined how various data sets (shire land values, forest plantation establishment and maintenance costs, and sequestration rates across shires) can be combined to generate estimates of the cost of sequestration and the associated shire-level costs of generating ACCUs. Drawing on these data sets, each shire's cost of generating ACCUs is displayed in Figure 5 whilst the region's marginal cost of generating ACCUs based on constrained reforestation, social and political considerations (later explained), is shown in Figure 6.

The most cost-effective sites for carbon sequestration via reforestation are either in the marginal farming areas in the east and south-east of the region, as well as the higher rainfall southern fringes of the region. In the southern parts, ACCUs in the range 250–350 tonnes of CO_2-e per hectare are possible and farmland in some shires remains relatively affordable, commonly in the range \$2500 to \$4000 per hectare. Other shires in the higher rainfall zone (>650 mm of annual rainfall) are less cost-effective sites because, despite their sequestration ability being higher, their land is much more expensive, bid up by being adjacent to major tourism and regional centres like Busselton and Albany.

Several shires in the lower rainfall east and south-east of the region (annual rainfall less than 350mm) are also cost-effective sites for sequestration via reforestation. Despite their sequestration rates being very low, their land costs are sufficiently low to make them cost-effective sites for sequestration. For example, farmland in the shire of Yilgarn at the edge of the grainbelt has a low rate of generating ACCUs (2.6 t CO_2-e/ha/yr) and low land values (<\$650 per hectare), making some of its land suitable for cost-effective sequestration.

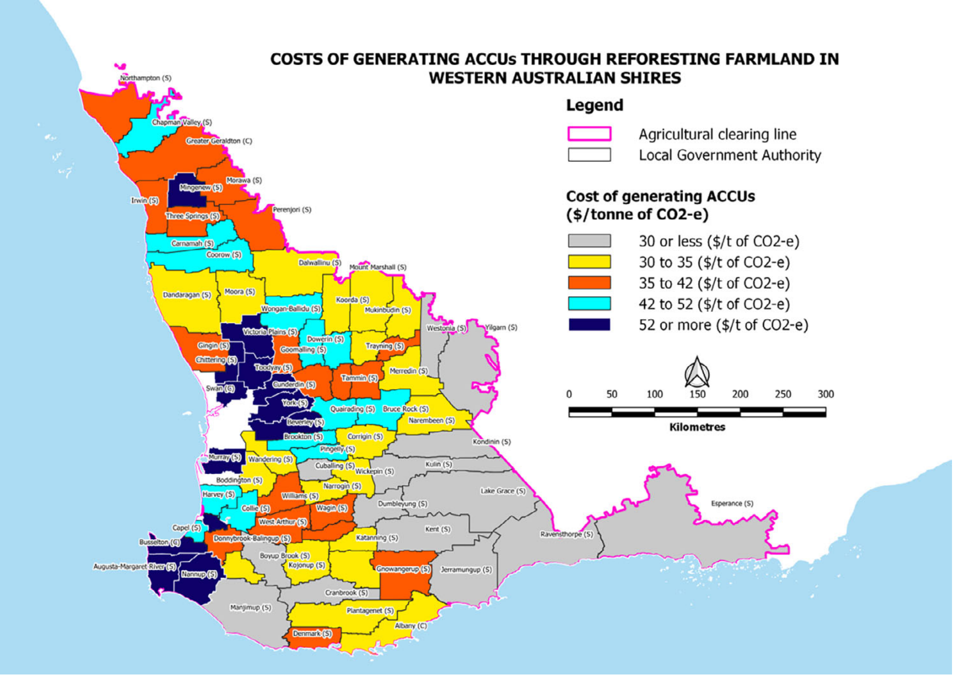

Figure 5 Cost of generating ACCUs through reforestation of arable land ($/t of CO_2-e). [Colour figure can be viewed at wileyonlinelibrary.com]

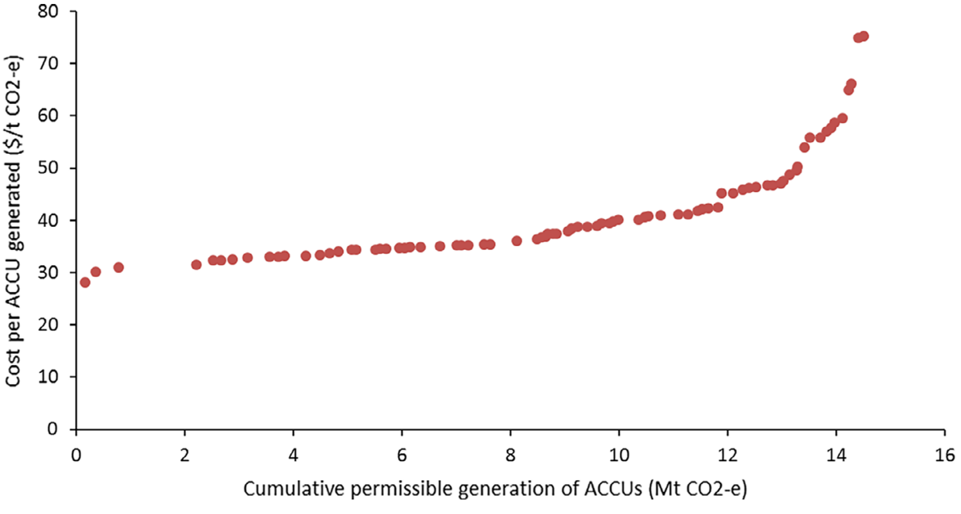

Figure 6 Marginal cost of generating ACCUs based on constrained reforestation of farmland in WA ($ per tonne of CO_2-e sequestered annually). [Colour figure can be viewed at wileyonlinelibrary.com]

The findings in Figure 5 are supported by observed forest-based carbon stock changes in the agricultural region of WA from 1990 to 2016 (see figure 6.8 in DISER (2020d)). The largest gains in forest-based carbon stocks reported by DISER (2020d) have occurred in the central and southern parts of the study region whilst its northern parts have recorded erosion of carbon stocks.

The set of least-cost shires for sequestration do differ from those identified by Harris-Adams and Kingwell (2009). The reason for more southerly and eastern shires being in the least-cost set of shires, rather than central shires as identified by Harris-Adams and Kingwell (2009), is due to a range of changes in land values, especially in the 2010s, and rainfall trends since the mid-1970s that have further decreased likely sequestration rates. For example, during the 2010s land values in the eastern wheat belt declined relative to values in most other regions, increasing their relative attractiveness for sequestration investment. Rural Bank (2019) reports that the northern parts of the study region recorded the largest growth of 34 per cent in the median price per hectare in 2018 compared to 2017, whilst the eastern parts of the study region recorded an average 12.3 per cent decline in their median price of farmland.

As outlined in the *Method* section, the data behind Figure 5 can be combined with other data sets to form a marginal cost of abatement curve (Figure 6). In practice, data in Figure 6 are subject to far greater uncertainty than suggested, due to variation in land prices within shires and across time, and due to variation in sequestration rates within shires and across time as rainfall and temperature trends alter. In Figure 6, the marginal cost of abatement rises as sequestration becomes either less technically feasible or the cost of land on which sequestration is proposed becomes too expensive relative to the carbon able to be stored in trees grown on that land. The marginal cost of generating ACCUs commences at around $30 per tonne of CO_2-e sequestered annually. Each data point in Figure 6 refers to a particular shire in the study region. Some shires displaying very high sequestration costs are not included in Figure 6.

A key assumption underlying Figure 6 is the political and social constraint that only up to 25 per cent of the arable area in any shire is permitted to be converted from farmland into reforestation. This issue is addressed in the next sub-section that presents the LP modelling results.

The data in Figure 6 indicate that almost 8 million ACCUs are estimated as being able to be generated annually at an annual cost of $35 per tonne of CO_2-e. Agricultural shire emissions in WA in 2015 were under 8 million tonnes of CO_2-e and so as revealed in Figure 6, all the region's agricultural emissions could be abated at an ACCU price of under $35; but this price is double the observed prices in ERF abatement auctions in 2020 (CER, 2020).

3.4 The region's spatial abatement opportunities

Applying the LP model described in the *Method* section of this paper yields the results in Table 2. However, these results need to be viewed with some caution, especially at the higher proportions of abatement of agricultural emissions (values of q) and where larger proportions of farmland are

Table 2 Optimal abatement scenarios based on reforestation

Percentage of farmland in each shire that can be devoted to sequestration (%) (i.e. p in the LP model)	Percentage of total annual agricultural emissions abated (%) (i.e. q in the LP model)	The region's annual agricultural emissions (kt CO_2-e)‡	Annual abatement in the region (kt CO_2-e)	Annual cost of abatement in the region ($m)	Proportion of all shires selected for sequestration activity (%)
100†	100	6556	6556	196.9	7
10	100	6722	6722	249.5	91
15	100	6739	6739	226.2	49
20	100	6696	6696	219.6	31
25	100	6659	6659	216.0	25
10	75	6886	5165	177.8	60
15	75	6863	5148	169.1	31
20	75	6889	5167	165.6	24
25	75	6860	5145	163.0	16
10	50	7067	3534	115.7	33
15	50	7072	3536	112.4	20
20	50	7055	3528	110.1	11
25	50	7065	3533	108.8	9

†This assumes no political or social restrictions apply to reforesting all farmland in any shire.
‡This is the sum of emissions from all shires in 2020 that underpins Figure 1 and is the spatial equivalent of Figure 2 but for the year 2020.

reforested (values of p). The need for caution arises from acknowledging that once the most cost-effective shire locations for sequestration are identified (and assuming it is legally and politically permissible to switch large swathes of farmland into forestry) then the price of land in those shires would be bid up, increasing the cost of sequestration and potentially making those shires no longer part of the set of shires that are cost-effective providers of abatement. Moreover, if future climate change is even more adverse than the warmer, drier climate observed since the 1970s, upon which this study's tree growth estimates are based, then future sequestration rates in many shires may be lower (Thamo et al. 2019) which will increase the cost of sequestration. Moreover, if innovation in dryland agriculture continues to underpin the profitability of farming, particularly in medium and high rainfall regions (Hochman & Horan, 2018), then further real appreciation in land prices for agriculture is feasible, raising the opportunity cost of land committed for abatement.

An important caveat is that the calculations underpinning Table 2 exclude any future reductions in emissions that might occur through any further reduction in ruminant livestock numbers or by the development of innovations that facilitate on-farm reductions in emissions (e.g. Roque et al. 2019; Vyas et al. 2016). Moreover, underpinning the results in Table 2 is the bold assumption that the agricultural industries across the study region act to cost-effectively procure sequestration services within the entire region. A more likely scenario, at least initially in the absence of a well-functioning carbon market, is that individual farms may make commercially verifiable investments in abatement in the hope of receiving price premia for agricultural products that can be branded as carbon neutral, thereby enabling access to markets that require those sustainability credentials. These farm businesses may make investments in least-cost reforestation in shires already identified. Conversely, some of these businesses may choose to offset their emissions in sequestration on farmland within their local shire because they can more easily visually monitor their investment.

Table 2 shows the unsurprising result that the higher the proportion of emissions that need to be offset via reforestation, the greater the cost to agriculture in the region. Also, the higher the proportion of agricultural emissions that need to be offset, the greater is the number of shires providing sequestration services. The preferred shires for sequestration investments are mostly in the more southerly, far eastern and south-eastern parts of the agricultural region. The locations of some of these highly preferred sites accord with statements in previous policy reports. For example, the CPRS White Paper (Commonwealth of Australia, 2008a) stated that the impacts of the CPRS would be such that 'The Government therefore expects that most forests established as a result of the Scheme will be not-for-harvest forests grown on marginal or less productive farm land,...' (p. 6–48); and 'new forests are likely to be established on more marginal or less productive agricultural land and will not undermine food security'. (p, 6–49). Ford et al. (2009) also reported the likelihood of forestry being placed on marginal farmland. These statements that marginal and less productive farmland would be targeted for sequestration are supported to some extent by the analysis in this study.

We find in addition that farmland in marginal areas is not the sole preferred target for sequestration investments. Rather, it is also farmland in traditionally reliable agricultural shires (i.e. the southern regions of WA's wheat-sheep belt; see Figure 5) that are also likely targets for reforestation. Although pockets of cheaper land in many shires may be cost-effective sources of reforestation, nonetheless our main finding is that some farmland, other than farmland in some marginal areas, mostly southern rainfall agricultural shires are also attractive initial options for reforestation. These southern shires often have more livestock in their farming systems and therefore higher levels of emissions (Figure 2). So, an added benefit of reforesting their farmland is a greater decrease in emissions through reduced availability of farmland to carry livestock. Also, tree growth rates in these southern shires are much higher than in low rainfall marginal areas, yet their farmland prices continue to mostly reflect agricultural profitability rather than the spillover effects of tourism, hobby-farming, holiday-making or urbanisation, as in other higher rainfall locations.

The scenario requiring carbon neutrality for the region's agriculture involves land use changes that further reduce the region's agricultural emissions by around 10 per cent whilst imposing additional annualised costs of emissions abatement of between AUD216 and AUD250 million.

Reforestation becomes a new or increased land use activity in 25 to 91 per cent of the region's shires. The range of the annualised cost of achieving carbon neutrality represents between 2.6 and 3 per cent of the state's gross value of agricultural production which suggests the target of carbon neutrality is within commercial reach. However, this cost, when translated into impacts on farms' business profit indicates that for the approximately 5800 (ABARES, 2020) broadacre and dairy farms in the study region responsible for the bulk of the regions' agricultural emissions in the region, their annual farm business profit is likely to decline by between 15 to 17 per cent (see Appendix S1). For these farm businesses, such a decline represents a sizeable financial impost.

The transferability of this study's findings to other main agricultural regions of Australia requires some comment. It is likely that the cost of providing regional abatement in New South Wales and Victoria may be much higher as these states contain 16 and 15 per cent of Australia's cattle population, whereas WA houses only 8 per cent of the nation's cattle. Also, New South Wales and Victoria accommodate 55 per cent of the nation's sheep population. This means that their enteric emissions will be far greater, plus their farmland is more expensive than in WA. These factors, in combination, suggest that the impact on farm profits from achieving carbon neutrality via reforestation could be much greater in these states.

Crossman et al. (2011) examined monoculture and mixed species plantations for carbon sequestration in South Australia's agriculture region that is not too different from the south-west agricultural region of WA. They reported that at a carbon price as low as AUD15 per tonne of CO_2-e it was profitable to switch 40–60 per cent of all farmland into plantations. For a group of 42 farms in the study region, Tang et al. (2021) found that during the period 2006 to 2013 a similar low price of AUD17.60 per tonne CO2-e should have triggered reforestation. Our results differ greatly, indicating that profitable land switching from agriculture into plantations is only feasible at much higher carbon prices (see Figure 6). Our results are in close accord with those of Thamo et al. (2013) who examined the impact of emission pricing on a typical mixed enterprise farm business in the heart of the study region. They found that if on-farm emissions were required to be offset, then at an initial carbon price of AUD23 per tonne of CO_2-e, the profit of the optimal farming system fell by 25.7 per cent. Given the lower carbon price assumed in this study the likely impact on reductions in farm profit would be less, especially also noting that since undertaking their study, the typical farm they examined has decreased further its sheep numbers and slightly increased its crop area which would have reduced the farm's emissions (Planfarm, 2019).

3.5 Sensitivity analysis

Modelling results are often underpinned by a range of assumptions, so results can change when different assumptions apply. Hence, a sensitivity analysis is required to reveal the robustness of findings. Accordingly, three key assumptions are varied: (i) the opportunity cost of farmland for sequestration, (ii) the magnitude of political and social constraints on reforestation, and (iii) the cost of plantation establishment. The sensitivity analysis results are displayed in Table 3.

A lower or higher opportunity cost of farmland decreases and increases, respectively, the cost of achieving carbon neutrality. Similarly, lower costs of establishing multi-species forests reduce the costs of delivering carbon neutrality. Lastly, the less restrictive are the social and political limits for switching farmland into reforestation, the lower is the cost of attaining carbon neutrality. Across the scenarios examined, the annual cost of abatement needed to deliver carbon neutrality ranges from AUD93 million to AUD222 million with the proportion of the shire population involved in reforestation ranging from 7 to 25 per cent.

3.6 Caveats

A first key caveat to our findings is that this study makes no allowance for farmers in the region being able to purchase cheaper offsets outside the

Table 3 Sensitivity analysis results[†]

Scenario	Percentage of farmland in each shire that can be devoted to sequestration (%) (i.e. *p* in the LP model)	The region's annual agricultural emissions (kt CO_2-e) that are abated by reforestation	Annual cost of abatement in the region (AUDmillion)	Proportion of the shire population selected for sequestration activity (%)
Farmland 2% real opportunity cost and standard establishment costs	100[‡]	6361	108.9	7
	50	6564	115.9	11
	25	6624	123.7	25
Farmland 2% real opportunity cost and lower establishment costs	100[‡]	6437	93.0	7
	50	6594	98.8	14
	25	6663	104.0	24
Farmland 5% real opportunity cost and standard establishment costs	100[‡]	6656	195.4	7
	50	6685	209.6	15
	25	6738	222.1	23
Farmland 5% real opportunity cost and lower establishment costs	100[‡]	6741	165.2	7
	50	6671	179.9	14
	25	6780	195.2	25

[†]All scenarios in Table 3 require carbon neutrality to be achieved (i.e. $q = 1$ in the LP model).
[‡]This assumes no political or social restrictions apply to reforesting all farmland in any shire.

farming region. For example, one such option would be to purchase pastoral leases and gain access to offsets or offset income via altered fire management on these leases (CER, 2018).

The opportunity cost of farmland, costs of establishing and maintaining forestry plantations, prices of other abatement activities and the cost and effectiveness of new farm practices for reducing emissions (e.g. Eckard et al. 2010), in combination, will affect farmers' decisions about land use. In this study, a real opportunity cost of farmland capital of 4 per cent was used to reflect land lease costs. However, landholders may demand an even greater premium for reforestation, due to the permanency of the land use change and the perceived undesirable social costs associated with converting farmland into forestry. This will raise the marginal cost of abatement and make abatement more expensive as shown in Table 3. Also, if political and social pressures further reduce the proportion of farmland in any shire that potentially could be reforested, then this will also raise the marginal cost of abatement within the study region.

The price premium sought by farmers to allow their land to be permanently reforested may not be uniform among farmers. Some low-emitting, risk-averse landholders may find attractive the prospect of not only abating their farm emissions but also increasing their investment in reforestation to provide a constant income stream from the permanent lease of some of their land for sequestration services for other farmers. Also, some farmers may have some parcels of farmland that are only marginally profitable for agriculture, yet are better suited for reforestation and are much lesser priced than other more fertile farmland. Such farmers might be the initial providers of sequestration services.

No account is taken of the effect on farmland valuations of investments in reforestation. Farmers who commit to such investments affectively reduce the size of their agricultural operations and pass on to any buyers of their farm the lease income but also the contractual obligation to maintain the investment in reforestation. Depending on the nature of the sequestration contract, buyers of the property may perceive they are purchasing either an asset or a liability. A related caveat is that the analysis assumes contracts are based on annualised tree growth rates rather than the actual dynamics of sequestration where in the early and later years of a tree's life little storage of carbon occurs.

No account is taken of any price changes in agricultural markets due to reduced agricultural production caused by reforestation. Favourable price increases in commodity markets would increase the opportunity cost of switching land away from agricultural production. However, the bulk of the region's agricultural production is exported and so farm-gate prices are not highly sensitive to alterations in local levels of production.

No account is taken of any additional benefits to soil carbon under a switch into permanent forestry, although these benefits are likely to be small (Hoogmoed et al. 2012; Paul & Polglase, 2004) and no account is taken of bushfires that remove sequestered carbon, other than the 5 per cent risk-of-reversal buffer. Also overlooked is the role of technological progress whereby tree provenance selection, improved planting and tree survival may lessen tree establishment costs and accelerate tree growth leading to lower unit costs per ACCU. Also, overlooked is the dynamics of investment in reforestation whereby farmers may opt to buy land and sell land for sequestration during periods when farmland prices are depressed due to extended droughts or a prolonged period of depressed prices for farm products. Lastly, the fragility of the chain of actions that underpins sequestration is not stressed. Pannell et al. (2018) point out that to affect an environmental change, sequestration being one example, often depends on a chain of activity involving environmental research, policy design and implementation, behaviour change and lastly environmental change. Each stage presents challenges and entails time lags. If any link fails, the chain breaks. So, cost-effective sequestration depends on a range of actions including research into tree species' suitability in different landscape settings, accurate low-cost measurement of tree growth and sequestration estimation, contract design and enforcement and estimation of any co-benefits from multi-species sequestration plantations.

The cost to farmers of ensuring the carbon neutrality of their farm production could be lessened if governments paid for additional environmental co-benefits generated by reforestation (e.g. wildlife corridors, greater biodiversity, landscape amenity, tree shade to improve animal welfare); or if consumers paid price premiums for the carbon-neutral status of the region's agricultural products or if greater market access occurred due to the carbon neutrality of the farm products. Carbon forestry projects that reward generated co-benefits (e.g. biodiversity, water and nutrient management) enhance their viability and adoption (Dumbrell et al. 2016; Torabi et al. 2016).

If carbon neutrality was sought for particular agricultural industries in the region, then the magnitude of the challenge would be less for grain farms and greater for livestock farms due to emissions per unit value of grain production being far less compared to those for livestock products (Eady et al. 2011). This issue of enterprise differences is not addressed in this study, but will be of crucial concern to farming communities that often comprise farm businesses ranging from crop-only enterprises through to livestock dominant businesses. Lastly, this study takes no account of emission-reducing technologies in development or further changes in farming practices that lessen emissions.

4. Conclusion

The need to reduce greenhouse gas emissions in agriculture is well recognised, as is the sector's role as a potential source of abatement via land use change (e.g. reforestation). However, there is currently little appreciation of the feasibility and cost of achieving carbon neutrality for Australia's main agricultural industries and regions.

This study addresses this lack of knowledge using the illustration of agricultural emissions and abatement in Western Australia's agricultural region in the south-west of Australia. The main sources of emissions predominately occur in the south of this region, where livestock dominate and higher crop input farming systems operate. The lowest emitting shires are mainly in the northern wheat belt, where the sheep population has been greatly reduced. Since 1990, almost all shires have displayed a downwards trajectory in their agricultural emissions. A substantial decline in the sheep population in many shires is the key cause of the decline in emissions. Three-quarters of shires are poised to qualify as fulfilling Kyoto Protocol obligations. In addition, 56 per cent of all shires currently are on track to satisfy the Paris Agreement emissions reduction target.

An examination of agricultural shires' abilities to be sources of emission abatement via reforestation identified several shires in eastern and southern marginal areas to be cost-effective locations for emission abatement through reforestation, along with several shires in higher rainfall southerly locales. Large amounts of ACCUs based on reforestation could be generated within the cost range of AUD30 to AUD35 per tonne of CO_2-e, and all agricultural emissions in the region could be sequestered at a price under AUD35 per tonne.

Because of the marked reduction in the region's agricultural emissions since 1990, the magnitude of the financial and technical challenge to ensure the region's agricultural industries are carbon neutral is lessening. The current analysis which is subject to a range of important caveats suggests that carbon neutrality of agriculture in the region could be achieved through a regional investment in reforestation that would cost the region's agricultural industries between AUD216 and AUD250 million annually, which amounts to between 2.6 and 3 per cent of the state's gross value of agricultural production or an estimated 15 to 17 per cent drop in farm business profit.

In practice, the actual cost of creating carbon neutrality would be higher if greater restrictions on land use change applied to satisfy political and social pressures, or if a rebuild of sheep and cattle numbers occurred, or if the relative profitability of retaining farmland for agriculture widened against using farmland for sequestration. It could also be less through (i) offsets being bought or generated from outside the agricultural region; (ii) technical innovations that reduce agricultural emissions; (iii) price premia or additional market access being generated by farm products marketed as carbon neutral; or (iv) governments paying for co-benefits associated with reforestation. Subject to these important caveats, this study's key finding is that the region's agricultural industries could achieve carbon neutrality via reforestation (at current ACCU prices), at an annual financial cost equivalent to a 15 to 17 per cent decline in farm business profit.

Despite this finding, the sentiment to support carbon neutrality is rising both from within agriculture itself (Beattie, 2020; GrainGrowers, 2020; MLA, 2019; NFF, 2020) and outside agriculture via social licence pressures from domestic consumers and policy actions by governments (Button, 2020). Results from this study suggest that if the Western Australian farm sector aimed for carbon neutrality and if its achievement was solely paid for by agricultural businesses undertaking forestry-based sequestration within their farming region, then the annual aggregate financial cost to these farm businesses would range from AUD216 to AUD250 million.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1 The impact on the region's farm business profit of gaining carbon neutrality via reforestation.