

# Soil acidity, lime application, nitrogen fertility, and greenhouse gas emissions: optimizing their joint economic management<sup>1</sup>

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## Highlights

- Complex economic interaction between soil acidity, nitrogen fertility, and GHG emissions
- Nitrogen fertilizer emits GHGs directly, and via higher lime rates to treat acidity
- Rates of nitrogen and lime affected by type of fertilizer, legume rotation, and rainfall
- Carbon pricing reduces GHG emissions from lime and nitrogen but only modestly
- Small social benefit of carbon pricing in this study but also small costs to farmers

## **Abstract**

Soil acidity is a major limiting factor for crop production in many farming systems worldwide. Lime application is the most common practice to mitigate soil acidity. There are complex economic interactions between application of lime and nitrogen fertilizer, with the greenhouse gas emissions associated with the use of these inputs adding further complexity. We employ a non-linear dynamic optimization model to determine economically optimal application strategies for lime and nitrogen fertilizer accounting for the social cost of the resulting emissions of greenhouse gases. The model is applied in three zones with different rainfall levels, in the northern wheatbelt of Western Australia. Rainfall has important influences on results through its effect on the dissolution and leaching of lime, leaching of nitrogen, and the yield potential of crops. Results show that nitrogen-related decisions, such as the type of nitrogen fertilizer and crop rotation, have a substantial impact on optimal lime application rates and resulting emissions. For example, the use of ammonium sulfate, rather than urea, reduces emissions. Similarly, by allowing a reduction in nitrogen fertilizer use the incorporation of legume crops like lupin can reduce emissions by 50 percent, relative to a wholly non-legume crop rotation. Although carbon pricing reduces emissions, the magnitude of the reductions is modest in all modeled scenarios. The private cost to farmers of a carbon tax in this case study region is small, although the net social benefit of the carbon tax in this case study is smaller still, even without accounting for the transaction costs of operating the tax system.

## **Keywords**

Carbon pricing; emissions; lime application; nitrogen; optimization; soil acidity.

## 1. Introduction

Around four billion hectares of land in the world are acidic (Baligar et al. 2001). Soil acidity is a major factor limiting crop yields. The main reason for decreased plant production on acid soils is an imbalance in macro and micro elements in the soil, including toxicity from an excess of hydrogen ( $H^+$ ) and/or aluminum ( $Al^{3+}$ ) (Moore 2001).

In Australia, losses in agricultural production from soil acidity were estimated in 2005 at A\$1,585 million per year (Hajkowicz and Young 2005). A more recent economic analysis by Petersen (2015) found that sub-soil acidity costs Western Australian grain growers about A\$1.6 billion per year in lost production.

A key cause of soil acidification is the application of nitrogenous fertilizers (Caires et al. 2006; Grennfelt and Thörnelöf 1992). Global usage of nitrogen fertilizer between 1960 and 1995 increased seven-fold and is expected to increase another three-fold by 2050 (Tilman et al. 2002) through increased cropping intensity.

Lime ( $CaCO_3$ ) is widely used to amend soil acidity (Dodgshon 1978; Holland et al. 2018). Lime application is an investment in soil productivity. It has been estimated that the average returns to investment in the lime application in the study region are A\$63 per hectare annually or A\$11 for each A\$1 invested (Petersen 2015). The combined effects of lime and nitrogen fertilizer are complex. Most studies have concluded that lime and fertilizer are complementary inputs (Bekele et al. 2018; Holland et al. 2018; Tumusiime et al. 2011; Wang et al. 2003). However, contrasting results have been reported by Bolton et al. (1976). Nitrogen fertilizers, especially ammonium-based fertilizers, increase soil acidity over time (Gazey et al. 2013). This may affect optimal liming strategies.

Lime dissolves in soil moisture and increases calcium ( $\text{Ca}^{2+}$ ) and bicarbonate ( $\text{HCO}_3^-$ ) ions concentrations in the soil exchange complex. Consequently,  $\text{Al}^{3+}$  ions are replaced by  $\text{Ca}^{2+}$  ions and soil pH is increased because the acid hydrolysis of  $\text{Al}^{3+}$  is greatly decreased. Concurrently,  $\text{HCO}_3^-$  reacts with the available  $\text{H}^+$  to yield carbon dioxide ( $\text{CO}_2$ ) and water (Helyar and Porter 1989). These processes reduce the concentration of  $\text{H}^+$  (that causes soil acidity), and they mitigate  $\text{Al}^{3+}$  toxicity and  $\text{Ca}^{2+}$  deficiency, both of which inhibit crop growth.

Globally, agriculture accounts for around 11 percent of anthropogenic greenhouse gas (GHG) emissions (Fellmann et al. 2018). Within Australia, the figure is 13 percent (Climate Council 2018). As other sectors of the economy, such as electricity generation, reduce their emissions there is likely to be an increasing attention on the need to mitigate agricultural emissions. Indeed, some have suggested that in the longer-term, an ideal policy response could be to apply a carbon price to agricultural emissions (Garnaut 2011). A contributor to agricultural emissions is the  $\text{CO}_2$  produced when lime dissolves (West and McBride 2005). Emissions from lime dissolution vary depending on a range of factors, including soil characteristics, climate, and the quality of lime applied (Costa 2012; Hati et al. 2008; Paradelo et al. 2015; Shaaban et al. 2017). Lime application to acidic soils can also increase GHG emissions indirectly, by increasing grain production (Barton et al. 2014), resulting in higher optimal rates for nitrogen fertilizer.

Numerous studies have analyzed economically optimal ways to reduce agricultural emissions (e.g., Barton et al. (2014); Beach et al. (2015); Burney et al. (2010); Eory et al. (2013); Gibbons et al. (2014); MacLeod et al. (2015); Wang et al. (2014)). However, none of these studies has accounted for the complex economic interactions and interdependencies between lime and nitrogen fertilizer

applications linked to GHG emissions. In this paper, we aim to address this knowledge gap.

Our study's first contribution is to simultaneously optimize application strategies for lime and nitrogen fertilizer accounting for the external costs (externalities) of GHG emissions. The analysis employs a dynamic optimization model that maximizes the Net Present Value (NPV) of farm net income over the long term.

The second contribution is to examine the effects of carbon pricing on optimal lime and nitrogen applications, including the resulting impacts on GHG emissions from crop farms. Currently, there is no clear market price for GHG emissions in most countries, including Australia (Brown and Li 2019; Department of Environment and Energy 2014). However, the study investigates the impact of a potential future price, in the form of a tax on GHG emissions, a so-called carbon tax. From the analysis we estimate the net social benefits of a carbon tax on representative farms in the study area.

## **2. Method**

### *2.1. Study area and farming system*

The Western Australian wheatbelt has a Mediterranean climate, and its agricultural production depends on winter rainfall. The farming systems in this area are dominated by cropping. This wheatbelt region produces about 14 million tonnes of grain annually (Wilkinson 2018) and about 81 percent of the cropped area is sown to cereals (wheat and barley) mainly in rotation with narrow-leaved lupin, a legume, *Lupinus agustifolius* L., or canola, a non-legume, *Brassica napus* L. (Seymour et al. 2012). Average yields across the wheatbelt area are 2.2 t ha<sup>-1</sup> for wheat, 2.5 t ha<sup>-1</sup> for barley, 1 t ha<sup>-1</sup> for canola and 1.4 t ha<sup>-1</sup> for lupin (Bankwest 2018). The farms are large and highly mechanized.

Typical farm sizes in the northern wheatbelt are 1,000 to 15,000 hectares (Wilkinson 2018).

Based on Bankwest (2017), three zones from the north of the Western Australian wheatbelt with different levels of rainfall are chosen as the study area: low rainfall (<325 mm annual average), medium rainfall (325 to 450 mm annual average), and high rainfall (>450 mm annual average). Two crop rotations are represented: wheat-wheat-lupin (WWL) and wheat-wheat-canola (WWC). A range of other rotations are used in practice, but these two are widely used.

The nitrogen fertilizer types considered in the analysis are urea ( $\text{CO}(\text{NH}_2)_2$ , 46 percent nitrogen) and ammonium sulfate ( $(\text{NH}_4)_2\text{SO}_4$ , 21 percent nitrogen). These both cause soil acidification.

Dominant soil types in the study region are deep sands and shallow sandy duplex, both of which are inherently acidic. In our analysis we consider a variant of the former soil type—a yellow sandy-textured topsoil horizon over sandy-loam sub-soil horizons—which is a typical acidic soil in the study region.

## *2.2. Acidity in the study area*

More than half of the surface and sub-surface soils of the wheatbelt area are acidic, with aggregate costs of more than \$500<sup>2</sup> million per annum in lost production (Herbert 2009). Soil acidification is an ongoing problem (due to the removal of harvested produce and the leaching of nitrate) and, on many farms, the current rate of lime application is insufficient to reverse acidification (Gazey et al. 2014). Acidic soils in the region have relatively high levels of free  $\text{Al}^{3+}$ , meaning crops often suffer from  $\text{Al}^{3+}$  toxicity (Moore 2001).

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<sup>2</sup> In this study all prices are expressed in Australian dollar (AUD).

Farmers' decisions to apply lime are affected by several factors: (i) management factors, such as the crop rotation and the type of nitrogen fertilizer used, (ii) biophysical factors such as initial soil pH and rainfall level (Conyers et al. 1995; Evans et al. 2001; Goulding et al. 1989; Kirchhof et al. 1995; Liu et al. 2004; Scott et al. 1992; Wang et al. 1999), and (iii) economic factors, such as the cost of lime application, crop prices, and the farmer's access to funds (Edmeades et al. 1985; Gazey et al. 2014).

We initialize our model with three different types of acidic soil profiles: an acidic topsoil (0-10 cm), an acidic sub-soil (10-30 cm), and both an acidic top and sub-soil (0-30 cm) where 'acidic' is defined as an initial pH level of 4.6 for the 0-10 cm of soil horizon, 3.8 for the 10-20 cm horizon and 4.1 for the 20-30 cm horizon. Non-acidic soil horizons are assumed to have initial pHs of 5.8, 5.8 and 6.5, respectively, for the same three soil horizons (see Figure 1). All pH values in this study are pH measured in  $\text{CaCl}_2$ . Common practice in the region is to spread (broadcast) lime on the soil surface. However, lime is slow to move through the soil, so to speed up the neutralization of sub-soil acidity, an option is to incorporate lime into the sub-surface (Davies et al. 2015). In our model both options are possible: lime can be applied to the soil surface and/or incorporated into sub-surface soil (10-20 cm and 20-30 cm horizons).



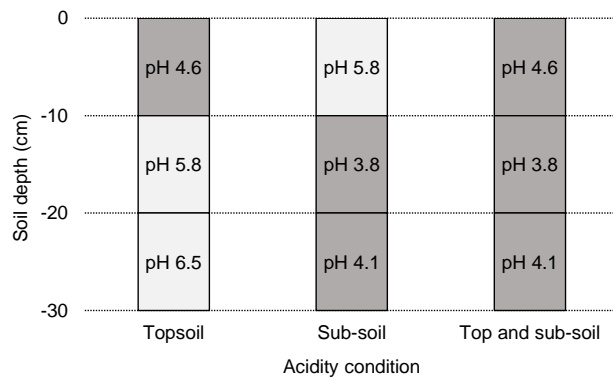


Figure 1. Initial soil profile diagram.

### 2.3. Model Structure

Our model is built in GAMS (General Algebraic Modeling System) and use the CONOPT solver to dynamically optimize lime and nitrogen fertilizer application rates for each rainfall zone of the study area and for each of the three types of initial soil profiles. The model structure is depicted in Figure 2; it is non-linear and has biophysical, GHG emissions, and economic components. Consistent with usual practice, GHG emissions are defined as units of weight of CO<sub>2</sub> equivalents (CO<sub>2</sub>-e) where one tonne of methane (CH<sub>4</sub>) equals 25 tonnes of CO<sub>2</sub>-e, and one tonne of nitrous oxide (N<sub>2</sub>O) equals 298 tonnes of CO<sub>2</sub>-e in terms of Global Warming Potential.

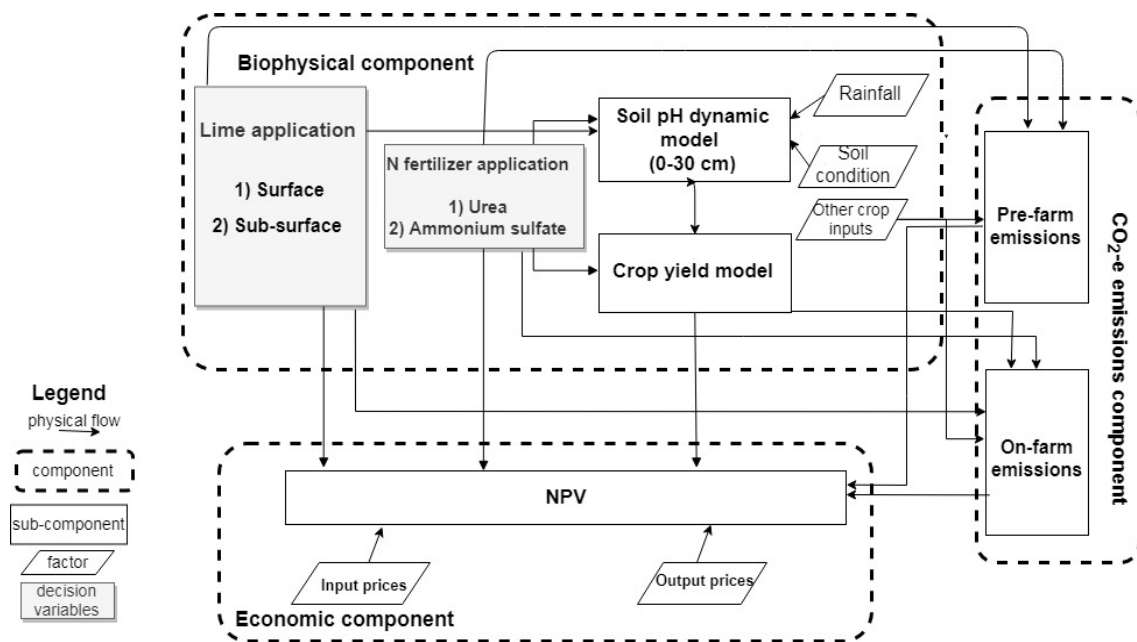


Figure 2. The model structure.

### 2.3.1. Biophysical component

The biophysical component is derived from the Optlime model (Gazey 2008). In Western Australia, Optlime has been widely used as a simulation model to investigate the long-term impacts of lime application on soil acidity over a 20-year planning horizon (Andrew and Gazey 2010; O'Connell et al. 1999). Its parameters are based on extensive research from across the grain-growing region. Limitations include that it does not determine the profit maximizing rate of lime application, it does not consider interactions between lime, and nitrogen fertilizer and greenhouse gas emissions, and it does not consider year-to-year climate variability.

The biophysical component consists of different interacting sub-components which are used to predict soil pH dynamics (across 0-10 cm, 10-20 cm, and 20-30 cm soil horizons) and crop yield. Captured in these pH dynamics are all processes associated with soil acidification in modern agricultural production: acidification from the application of ammonium-based nitrogen fertilizer, nitrogen

leaching and product removal, and countering this, the effect of lime applications, taking into account lime rate, quality, and application method (surface and/or sub-surface). Also captured in these dynamics are interactions with rainfall and soil properties (initial soil pH, buffering capacity, texture, soil gravel, organic carbon, and aluminum levels). In the original Optlime model, crop yield is a function of soil pH and rainfall. However, for the biophysical component of this model nitrogen nutrition has been added, so that crop yield is a function of soil pH, rainfall, and nitrogen fertility (from both fertilizer and legume rotations). In the case of lupin, no nitrogen is applied, and some of the nitrogen fixed by this leguminous crop carries over to benefit subsequent cereal crops. The modeling of nitrogen fertility (and the biophysical component more generally) is described in more detail by Shoghi Kalkhoran et al. (Under Review). In brief, yield in response to nitrogen application is modeled as a function of yield potential and nitrogen available for uptake in a given year, which depends on the nitrogen fertilizer rate, stable organic nitrogen and residue organic nitrogen from a previous legume crop. The response function to nitrogen fertilizer follows the usual shape for such functions, with a modest yield at zero fertilizer rate, increasing at a decreasing rate to a maximum yield.

### 2.3.2. Emissions component

The GHG component models the emissions associated with each rotation, as affected by lime and nitrogen fertilizer strategies. The total GHG emissions in year  $t$ , denoted as  $GHG_t$ , are calculated as:

$$GHG_t = (GHG_{pre_t} + GHG_{on_t})/1000 \quad (1)$$

where  $GHG_{pre_t}$  is the total emissions occurring 'pre-farm' (kg CO<sub>2</sub>-e ha<sup>-1</sup>) in year  $t$ , and  $GHG_{on_t}$  is the total emissions occurring on farm (kg CO<sub>2</sub>-e ha<sup>-1</sup>) in year  $t$ . Pre-farm means that the emissions occur prior to the inputs reaching the farm. The divisor 1000 converts the total CO<sub>2</sub>-e emissions,  $GHG_t$ , from kg CO<sub>2</sub>-e ha<sup>-1</sup> to tonnes CO<sub>2</sub>-e ha<sup>-1</sup>. The total pre-farm is given by:

$$GHG_{pre_t} = L_{PT_t} + N_{PT_t} + D_{PT_t} \quad (2)$$

where  $L_{PT_t}$  is the emissions from lime production and transportation in a given year (kg CO<sub>2</sub>-e ha<sup>-1</sup>);  $N_{PT_t}$  is the emissions from nitrogen fertilizer production and transportation in a given year (kg CO<sub>2</sub>-e ha<sup>-1</sup>);  $D_{PT_t}$  is the emissions from the production and transport of diesel fuel that is used on-farm in a given year (kg CO<sub>2</sub>-e ha<sup>-1</sup>).

Total on-farm CO<sub>2</sub>-e emissions are:

$$GHG_{on_t} = N_{DR_t} + N_{IDR_t} + R_{cr_t} + B_{cr_t} + U_{h_t} + D_{on_t} + L_{d_t} \quad (3)$$

where  $N_{DR_t}$  is the direct N<sub>2</sub>O emissions from nitrogen fertilizer application in a given year (kg CO<sub>2</sub>-e ha<sup>-1</sup>);  $N_{IDR_t}$  is the indirect N<sub>2</sub>O emissions from nitrogen fertilizer application in a given year (kg CO<sub>2</sub>-e ha<sup>-1</sup>);  $R_{cr_t}$  is the direct N<sub>2</sub>O emissions from crop residues in a given year (kg CO<sub>2</sub>-e ha<sup>-1</sup>);  $B_{cr_t}$  is the emissions from burning crop residues in a given year (kg CO<sub>2</sub>-e ha<sup>-1</sup>);  $U_{h_t}$  is the emissions from urea hydrolysis (a chemical reaction whereby urea reacts with the water in the soil immediately after application, releasing CO<sub>2</sub>) in a given year (kg CO<sub>2</sub>-e ha<sup>-1</sup>);  $D_{on_t}$  is the emissions from diesel that is combusted on-farm (kg CO<sub>2</sub>-e ha<sup>-1</sup>) to apply lime and nitrogen; and  $L_{d_t}$  is the emissions from lime dissolution in a given year (kg CO<sub>2</sub>-e ha<sup>-1</sup>).

Methods used to quantify the emissions from each of the sources listed above are provided in the Supplementary Information. Under the Tier 1 Intergovernmental Panel on Climate Change (IPCC) emissions accounting methodologies (IPCC 2006), all applied lime is assumed to dissolve, and thus all emissions from lime dissolution are assumed to occur, in the year of lime application. In reality, lime does not completely dissolve in the year of application, particularly in the conditions of the study area (e.g., Whitten et al. 2000). Dissolution rates depend on a number of interacting factors such as particle size, rainfall, and soil pH. Biophysically, whether the lime dissolves over one or many years may seem immaterial: the total emissions that will ultimately occur due to the dissolution will be the same. However, because of the time-value of money (and thus the effect of financial discounting), assumptions of near instantaneous dissolution inflate the apparent social cost of lime emissions. We therefore test two scenarios in this study for the emissions from lime dissolution: a) Scenario 1 (IPCC assumption): complete lime dissolution in the year of application. b) Scenario 2 (Optlime assumption): lime dissolution (and hence emissions) occurs at the rate predicted by biophysical component of our model (which is based on Optlime) in the years after lime application. Lime dissolution rate is one of the key processes captured in the Optlime model. More information on these scenarios is provided in the Supplementary Information.

Equations (2) and (3) do not capture all emissions associated with crop production in the study area. Not accounted for are the pre-farm emissions associated with the manufacture and transportation of non-nitrogen fertilizer, herbicides, pesticides, and farm machinery and the on-farm emissions from the diesel used for seeding, spraying, and harvesting. Whilst some of these can be substantial sources of emissions, they are omitted because the focus of our

analysis is the emissions associated with different break crops, lime, and nitrogen fertilizer strategies, and not with the totality of crop production in the study area. Most of the omitted emissions are unlikely to differ substantially between the different break crop, lime and fertilizer options we analyze (e.g., regardless of the choice between these options, a pass by the same tractor and machinery being used in exactly the same manner is required to sow the crop). Indeed, based on the results of lifecycle analysis of wheat, canola and lupin production in the Western Australian wheatbelt (Barton et al. 2014; Biswas et al. 2011) the omitted emissions are unlikely to differ by more than around 15 kg CO<sub>2</sub>-e ha<sup>-1</sup> yr<sup>-1</sup> between the different break crop, fertilizer, and lime strategies. Moreover, any differences between lupin and canola break crops would only affect one year of the three year rotations we analyze.

#### 2.4. Optimization

Through the integration of its three components, our model determines the dynamically optimal strategies for lime and nitrogen fertilizer application for each rotation, accounting for the cost of paying a carbon tax for each unit of emissions. This model maximizes NPV over an 80-year time horizon. This long timeline is used to allow the model to reach equilibrium. The dynamic optimization problem is written as:

$$\max_{\{L_{t,i} \text{ and } N_t\}} NPV = \sum_{t=1}^T \{[(p_{cr} \times Y_t) - (p_n \times N_t) - w_t - (p_c \times GHG_t)](1 + r)^{-t}\} + \sum_{t=T-\Psi}^T \frac{\{[(p_{cr} \times Y_t) - (p_n \times N_t) - w_t - (p_c \times GHG_t)](1+r)^{-t}\}}{((1+r)^{\Psi-1})} \quad (4)$$

subject to equations (1) to (3)

where  $NPV$  is the net present value of profit over the  $T$  (80) years ( $\$ \text{ ha}^{-1}$ );  $L_{t,i}$  is the lime rate applied to a given soil horizon  $i$  (0-10 cm, 10-20 cm and 20-30 cm) in year  $t$  ( $\text{t ha}^{-1}$ );  $p_{cr}$  is the price of grain from the crop grown in year  $t$  ( $\$ \text{ t}^{-1}$ );  $Y_t$  is the crop yield in year  $t$  ( $\text{t ha}^{-1}$ );  $p_n$  is the price of the nitrogen fertilizer ( $\$ \text{ t}^{-1}$ );  $N_t$  is the nitrogen fertilizer rate applied in year  $t$  ( $\text{kg ha}^{-1}$ );  $w_t$  is the cost of lime application ( $\$ \text{ ha}^{-1}$ );  $p_c$  is the carbon tax ( $\$ \text{ t CO}_2\text{-e}^{-1}$ );  $GHG_t$  is the total emissions (both pre- and on-farm) in year  $t$  ( $\text{t CO}_2\text{-e ha}^{-1}$ );  $r$  is the real discount rate, which is set to 0.05; and  $\Psi$  is the frequency of maintenance lime applications, which is every 10 years. The second part of Equation (4) is a terminal value function; it is the NPV of the last  $\Psi$  years of the planning time horizon, repeated to infinity to capture economic values of lime and nitrogen fertilizer application after the time horizon.

The model's decision variables are the lime application rate for year one (corrective rate), subsequent 'maintenance' lime rates, and also the optimal nitrogen application rates for wheat and canola (the leguminous lupin does not require nitrogen fertilizer). Maintenance lime applications are assumed to occur at 10-yearly intervals (intervals of 5 and 20 years were also tested and it was found that the economic performance of the system is highly unresponsive to different liming intervals). To increase the model's tractability when solving, the maintenance rates of lime application are constrained to be the same each time. Similarly, nitrogen fertilizer application rates are constrained to be the same for each given crop phase in the rotation (e.g., for every wheat crop that is the first wheat crop after a year of lupins, the rates are the same).

The model input and output prices are assumed to remain constant in real terms for the duration of the time horizon. The prices of wheat, lupin, canola, and urea

are set at \$241, \$247, \$475 and \$660 t<sup>-1</sup> (Thamo et al. 2017). The price of ammonium sulfate is set at \$400 t<sup>-1</sup>. Following Gazey (2008), the cost of lime application (lime-sand with 89.3 percent acidity neutralizing value) is calculated as:

$$w_t = \left[ L_{t,1} \times (\vartheta + d_1 \times \varphi) + L_{t,1} \times \left( \frac{7.4}{(L_{t,1} + 0.09)} + 4.9 \right) \right] + \left[ \sum_{i=2}^3 L_{t,i} \times (\vartheta + d_1 \times \varphi) + (\text{if } \sum_{i=2}^3 L_{t,i} > 0 \text{ then } 123.72) \right] \quad (5)$$

where  $L_{t,1}$  is the lime rate applied in a given year  $t$  to the soil horizon 0-10 cm (t ha<sup>-1</sup>);  $\vartheta$  is the purchase price of lime at the quarry, set at \$10 t<sup>-1</sup>;  $d_1$  is the average distance for the lime freight from the lime source to the quarry, which is assumed to be 100 km;  $\varphi$  is the freight rate, set at \$0.1 km<sup>-1</sup> t<sup>-1</sup>;  $L_{t,2}$  and  $L_{t,3}$  are the lime rates applied in a given year  $t$  to the sub-soil horizons 10-20 cm and 20-30 cm. It is assumed that the sub-surface lime application is split 50-50 between the sub-soil horizons. The cost of sub-surface lime application including ripping and then injecting bands of lime within the soil profile, labor, and depreciation of machinery is set at \$123.72 ha<sup>-1</sup> based on the advice of technical experts about current farm practices in the study area.

In addition to the cost of lime and nitrogen fertilizer, the cost of negative externalities caused by the emissions associated with the crop production can be deducted from the NPV. When calculating the cost of these externalities, a carbon tax of \$20 t CO<sub>2</sub>-e<sup>-1</sup> is assumed to apply to all emissions. This is similar to the \$23 t CO<sub>2</sub>-e<sup>-1</sup> used in the carbon tax mechanism implemented by the Australian government in 2012 (Meng et al. 2013) (and then repealed 2014). However, we examine the sensitivity of emissions to alternative carbon taxes within the range \$0 to \$70 t CO<sub>2</sub>-e<sup>-1</sup>.



## 2.5. *Net social benefit of a carbon tax*

As the objective function of the model provides a measure of farm profit, a comparison of the objective function with and without a tax on emissions provides an estimate of the cost to the cropping enterprise of the imposition of the carbon tax. However, this ignores the benefits to the community that are generated by the carbon tax. If we assume that the carbon tax is set at a level equal to the marginal social cost of carbon emissions, we can easily calculate the gross social benefits from a carbon tax policy, and we can then use the model results to estimate the net social benefits.

The conceptual framework for calculating the net social benefit of carbon pricing is depicted in Figure 3. It is assumed that the demand curve is perfectly elastic (horizontal), because changes in production by farmers in a region the size of our case studies would not appreciably affect the global market prices of grains. The supply curve, labeled marginal private cost (MPC), intersects with the demand curve at Q1, which is the privately optimal level of grain production. The introduction of a tax on carbon emissions raises the cost of crop production so the supply curve rises to MSC (marginal social cost) and crop production falls to Q2, the socially optimal level.

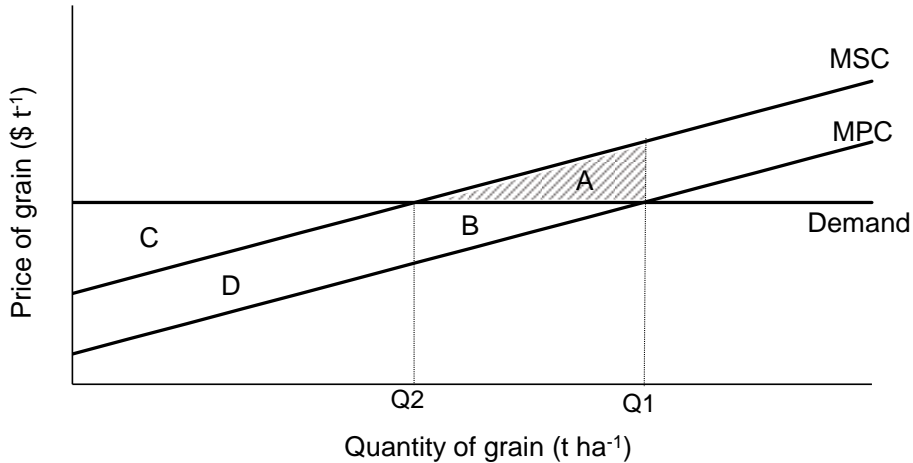


Figure 3. The net social benefit of carbon pricing (shaded area A).

The producer surplus ( $\approx$  profit) without the carbon tax is equal to the area C+D+B, and producer surplus falls to area C with a carbon tax in place. The social cost of emissions is D+B+A if there is no carbon tax (and farmers produce at Q1) and the social cost of emissions falls to D with the carbon tax in place, so the benefits from reducing the negative externalities are A+B. Area D in Figure 3 is the tax paid by farmers after they have adjusted their production down to Q2. (The tax is a transfer payment: the cost to farmers is cancelled out by a benefit to the rest of society as the collected revenue is able to be spent on beneficial activities or to substitute for other taxes.) Area B is a deadweight loss (a cost to farmers) from reduced crop production as a result of the tax. Combining all of these insights, we can see that area A is the net social benefit of the carbon tax. Assuming that the tax (and social cost) of carbon emissions ( $p_c$ ) is constant in real terms, this can be calculated as:

$$A = (p_c \times [\sum_{t=1}^T GHG_{t_{c0}} - \sum_{t=1}^T GHG_{t_{c1}}]) - B \quad (6)$$

where  $GHG_{t_{c0}}$  and  $GHG_{t_{c1}}$  are the total emissions ( $t \text{ ha}^{-1}$ ) over the  $T$  (80) years without and with carbon pricing and B is the deadweight loss from reduced

production. The latter can be calculated as the reduction in producer surplus minus the area D:

$$B = NPV_{c0} - NPV_{c1} - (\sum_{t=1}^T GHG_{t_{c1}} \times p_c) \quad (7)$$

### 3. Results and Discussion

The initial results are based on the official IPPC assumption that complete lime dissolution occurs in the year of lime application. We start by examining GHG emissions when the carbon tax is zero as a baseline. GHG emissions from on-farm and pre-farm sources vary depending on the nitrogen fertilizer type and the crop rotation (Figure 4). Total emissions are nearly 50 per cent higher for the canola rotation than for the lupin rotation because nitrogen fixation by the lupin crop allows less nitrogen fertilizer to be applied. This reduces emissions associated with fertilizer manufacture and transport, and also N<sub>2</sub>O emissions from fertilizer applications. Figure 4 shows the emissions associated with nitrogen fertilizer application are much more substantial than those associated with liming, so from an emissions perspective any practice that reduces nitrogen applications is beneficial (Brock et al. 2016). The on-farm sources contribute as much as three times more emissions than pre-farm sources.

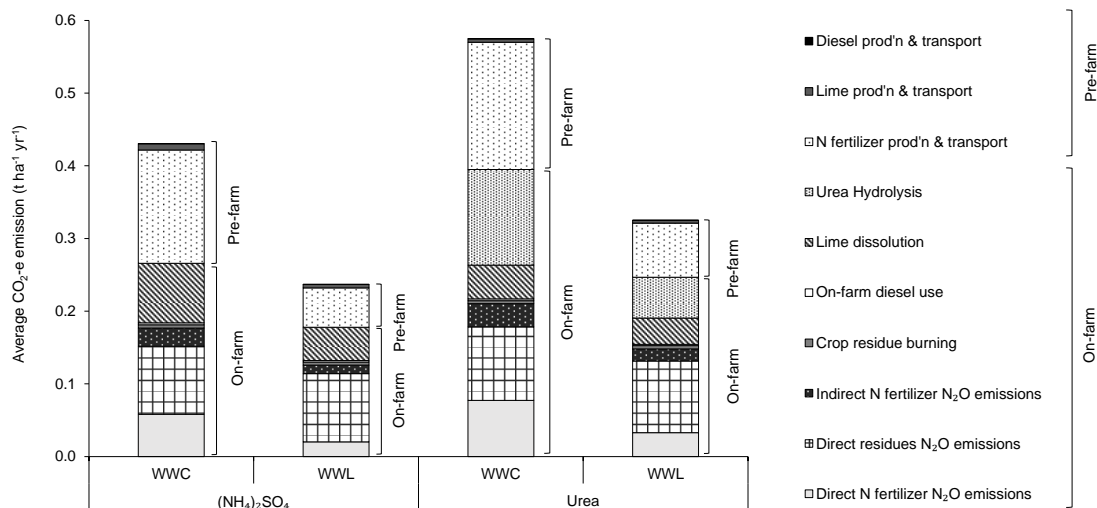


Figure 4. CO<sub>2</sub>-e emissions for the WWC and WWL rotations for different nitrogen fertilizer types and medium rainfall (325-450 mm) zone with top and sub-soil acidity condition under lime dissolution scenario 1 (IPCC assumption) when liming method is surface plus sub-surface application and the price of carbon emissions is zero.

Emissions are higher when urea is used as the form of nitrogen fertilizer, compared with ammonium sulfate. This is primarily because of additional emissions from the process of urea hydrolysis in the soil. There is no comparable process for ammonium sulfate. On the other hand, ammonium-based fertilizers are more acidifying, meaning that lime applications (and thus emissions associated with liming) are higher when ammonium sulfate is used (Figure 4).

Total emissions are between 0.303 and 0.764 t CO<sub>2</sub>-e ha<sup>-1</sup> yr<sup>-1</sup> for the WWC rotation and between 0.152 and 0.430 t CO<sub>2</sub>-e ha<sup>-1</sup> yr<sup>-1</sup> for the WWL rotation (Table 1). The reductions in emissions occur primarily in the lupin phase of the rotation, both in the year lupin is grown, and in following year when wheat is subsequently grown (Figure 5). With higher rainfall more nitrogen is applied, and nitrogen leaching and thus acidification is also greater. This means more

emissions from nitrogen application, and from liming to offset the acidification, and so on a per hectare basis emissions increase with rainfall in Table 1.

Table 1. Emissions for the WWC and WWL rotations when the carbon tax is zero. Results shown are for different rainfall zones with different soil acidity conditions under lime dissolution scenario 1 (IPCC assumption).

Annual rainfall (mm)	Acidity condition	Nitrogen fertilizer	Average CO <sub>2</sub> -e emission (t ha <sup>-1</sup> yr <sup>-1</sup> )	
			WWC	WWL
<325	Topsoil	Urea	0.375	0.215
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.303	0.152
	Sub-soil	Urea	0.411	0.233
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.352	0.179
	Top and sub-soil	Urea	0.405	0.232
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.325	0.180
325-450	Topsoil	Urea	0.556	0.305
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.410	0.218
	Sub-soil	Urea	0.572	0.321
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.428	0.232
	Top and sub-soil	Urea	0.576	0.325
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.431	0.237
>450	Topsoil	Urea	0.743	0.410
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.510	0.264
	Sub-soil	Urea	0.760	0.426
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.529	0.280
	Top and sub-soil	Urea	0.764	0.430
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.534	0.285

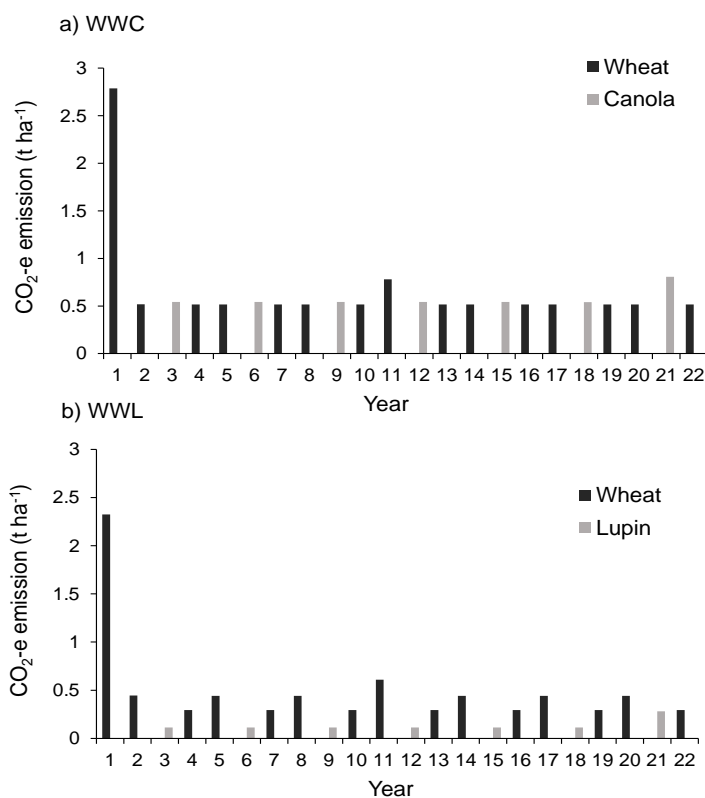


Figure 5. Emission for the WWC and WWL rotations in different years in medium rainfall (325-450 mm) zone with top and sub-soil acidity condition under lime dissolution scenario 1 (IPCC assumption) when nitrogen fertilizer is urea, liming method is surface plus sub-surface application and the carbon tax is zero.

Tables 2 and 3 present the optimal lime and nitrogen fertilizer rates, their associated emissions, and NPVs for the WWC and WWL rotations when the carbon tax is \$20 t CO<sub>2</sub>-e<sup>-1</sup> (numbers in parentheses show absolute changes for lime and nitrogen fertilizer rates, emissions, and the NPVs relative to carbon tax zero). Sub-soil acidity requires higher lime application rates than does topsoil acidity, and in many cases, the presence of sub-soil acidity means that sub-surface application of lime is worthwhile, despite its high cost relative to the surface application. Rates of both inputs are higher for the canola rotation (Table 2) than for the lupin rotation (Table 3).

The imposition of a \$20 t CO<sub>2</sub>-e<sup>-1</sup> tax on emissions reduces the optimal lime and nitrogen fertilizer applications and resulting emissions across all crop rotations, rainfall, and soil acidity conditions. Across all scenarios for the WWC rotation in Table 2, implementing carbon pricing reduces emissions by an average of 5.6 percent and up to 8 percent, and for the WWL rotation in Table 3 by an average of 6.4 percent and up to 10 percent. The WWL rotation still emits about half that of the WWC rotation, a similar proportion as when carbon tax is zero. Carbon pricing reduces the NPV of profits by an average of 3 percent and up to 4 percent for the WWC rotation (Table 2) and by an average of 1.7 percent and up to 2.2 percent for the WWL rotation (Table 3).

Table 2. Lime application and nitrogen fertilizer rates, emissions and NPV for the WWC rotation when the carbon tax is \$20 t CO<sub>2</sub>-e<sup>-1</sup> (numbers in parentheses show changes relative to carbon tax zero). Results shown are for different rainfall zones with different soil acidity conditions under lime dissolution scenario 1 (IPCC assumption).

Annual rainfall (mm)	Acidity condition	Nitrogen fertilizer	Lime application rate (t ha <sup>-1</sup> )			Nitrogen fertilizer rate (kg N ha <sup>-1</sup> )		NPV (\$ ha <sup>-1</sup> )	Average CO <sub>2</sub> -e emission (t ha <sup>-1</sup> yr <sup>-1</sup> )
			Surface (year 1)	Sub-surface* (year 1)	Surface maintenance (10 yearly)	Wheat	Canola		
<325	Topsoil	Urea	1.1 (-0.2)	- (0)	- (0)	53 (-2)	52 (-3)	\$6,356 (-151)	0.361 (-0.014)
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	1.8 (-0.1)	- (0)	1.0 (0)	41 (-2)	40 (-2)	\$5,865 (-126)	0.291 (-0.013)
	Sub-soil	Urea	- (0)	3.9 (0.1)	0.2 (-0.4)	52 (-2)	51 (-3)	\$6,155 (-176)	0.382 (-0.029)
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	- (0)	4.7 (-1.5)	1.6 (-0.2)	40 (-3)	39 (-3)	\$5,604 (-173)	0.324 (-0.029)
	Top and sub-soil	Urea	1.6 (-0.1)	3.0 (0)	0.3 (0)	52 (-3)	52 (-3)	\$6,125 (-184)	0.391 (-0.014)
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	3.0 (0)	3.5 (-0.2)	0.8 (-0.1)	41 (-2)	40 (-2)	\$5,619 (-164)	0.311 (-0.014)
325-450	Topsoil	Urea	1.0 (-0.1)	- (0)	0.6 (0)	78 (-5)	79 (-5)	\$6,979 (-218)	0.530 (-0.027)
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	2.2 (-0.2)	- (0)	1.4 (-0.1)	57 (-4)	59 (-4)	\$6,284 (-168)	0.387 (-0.022)
	Sub-soil	Urea	1.7 (0)	3.1 (-0.1)	0.5 (0)	77 (-5)	78 (-5)	\$6,765 (-248)	0.544 (-0.029)
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	3.1 (-0.2)	3.7 (-0.1)	1.3 (-0.1)	56 (-4)	58 (-4)	\$6,039 (-203)	0.403 (-0.025)
	Top and sub-soil	Urea	2.3 (0)	2.8 (-0.1)	0.6 (0)	77 (-5)	79 (-5)	\$6,751 (-251)	0.548 (-0.028)
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	3.3 (-0.1)	3.3 (-0.1)	1.3 (-0.1)	57 (-4)	59 (-4)	\$6,046 (-203)	0.407 (-0.023)
>450	Topsoil	Urea	1.3 (-0.1)	- (0)	0.9 (-0.1)	106 (-8)	102 (-8)	\$8,098 (-288)	0.698 (-0.045)
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	2.4 (-0.3)	- (0)	1.8 (-0.2)	72 (-7)	72 (-6)	\$7,212 (-204)	0.474 (-0.036)
	Sub-soil	Urea	1.9 (-0.1)	3.5 (-0.1)	0.9 (-0.1)	104 (-8)	101 (-8)	\$7,872 (-321)	0.713 (-0.047)
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	3.2 (-0.3)	3.9 (-0.2)	1.7 (-0.2)	71 (-7)	70 (-7)	\$6,961 (-241)	0.490 (-0.039)
	Top and sub-soil	Urea	2.6 (-0.1)	3.2 (-0.1)	0.9 (-0.1)	105 (-8)	102 (-8)	\$7,856 (-324)	0.718 (-0.046)
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	3.6 (-0.2)	3.5 (-0.1)	1.7 (-0.2)	72 (-7)	72 (-6)	\$6,962 (-242)	0.497 (-0.037)

\* This lime application is divided equally between the 10-20 cm and 20-30 cm soil horizons

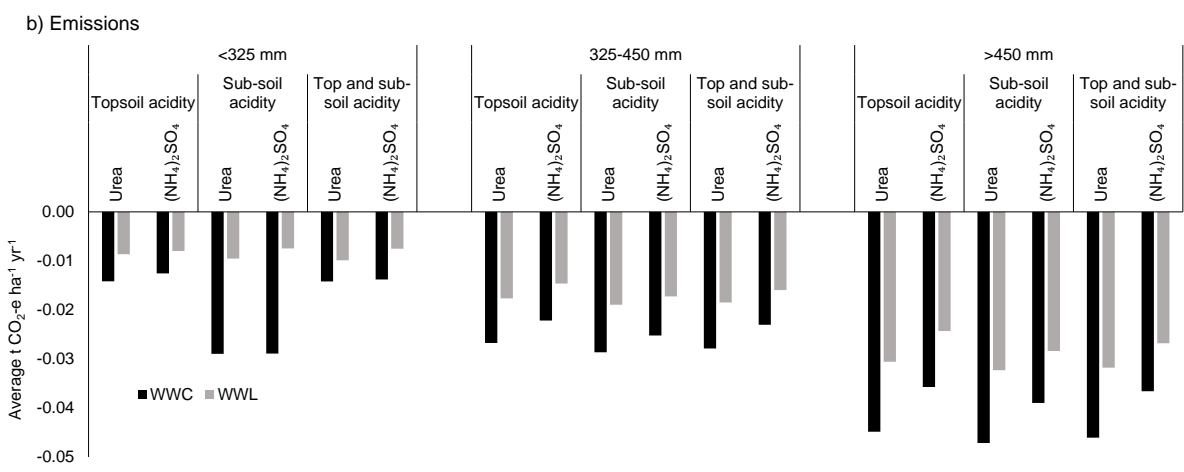
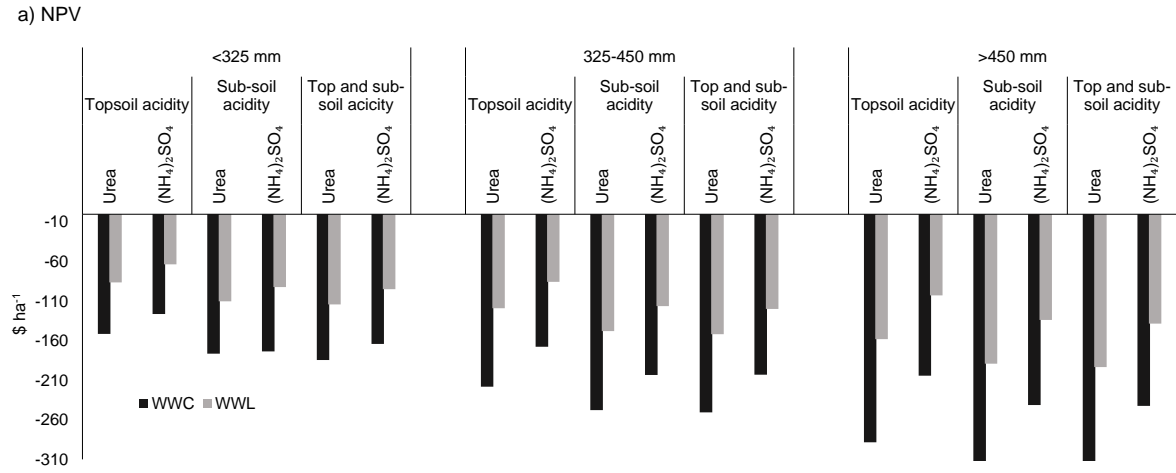
Table 3. Lime application and nitrogen fertilizer rates, emissions and NPV for the WWL rotation when the carbon tax is \$20 t CO<sub>2</sub>-e<sup>-1</sup> (numbers in parentheses show changes relative to carbon tax zero). Results shown are for different rainfall zones with different soil acidity conditions under lime dissolution scenario 1 (IPCC assumption).

Annual rainfall (mm)	Acidity condition	Nitrogen fertilizer	Lime application rate (t ha <sup>-1</sup> )			Nitrogen fertilizer rate (kg N ha <sup>-1</sup> )		NPV (\$ ha <sup>-1</sup> )	Average CO <sub>2</sub> -e emission (t ha <sup>-1</sup> yr <sup>-1</sup> )	
			Surface (year 1)	Sub-surface* (year 1)	Surface maintenance (10 yearly)	Wheat after lupin	Wheat after wheat			
<325	Topsoil	Urea	0.5 (-0.1)	- (0)	- (0)	25 (-2)	44 (-2)	\$6,276 (-86)	0.207 (-0.009)	
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.8 (-0.2)	- (0)	- (0)	12 (-2)	31 (-2)	\$6,083 (-63)	0.144 (-0.008)	
	Sub-soil	Urea	- (0)	3.2 (-0.1)	0.1 (0)	24 (-2)	43 (-2)	\$6,079 (-110)	0.224 (-0.009)	
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	- (0)	3.6 (-0.2)	0.3 (0)	13 (-2)	31 (-2)	\$5,866 (-92)	0.172 (-0.007)	
	Top and sub-soil	Urea	1.2 (0)	2.8 (-0.1)	- (0)	24 (-3)	43 (-3)	\$6,057 (-114)	0.222 (-0.009)	
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.9 (0.1)	3.2 (-0.3)	0.2 (0)	13 (-2)	31 (-2)	\$5,843 (-95)	0.172 (-0.008)	
	325-450	Topsoil	Urea	0.5 (-0.1)	- (0)	0.4 (0)	33 (-5)	63 (-5)	\$7,473 (-119)	0.288 (-0.018)
			(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.6 (-0.2)	- (0)	0.7 (0)	13 (-4)	43 (-4)	\$7,213 (-85)	0.204 (-0.015)
		Sub-soil	Urea	1.3 (0)	2.8 (-0.1)	0.4 (0)	32 (-5)	62 (-5)	\$7,258 (-148)	0.302 (-0.019)
(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>			1.6 (-0.1)	3.0 (-0.2)	0.5 (-0.1)	12 (-5)	41 (-5)	\$6,988 (-116)	0.215 (-0.017)	
Top and sub-soil		Urea	1.9 (0)	2.6 (-0.1)	0.4 (0)	33 (-5)	62 (-5)	\$7,243 (-152)	0.307 (-0.018)	
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	2.2 (0)	2.7 (-0.2)	0.5 (-0.1)	13 (-4)	42 (-4)	\$6,977 (-120)	0.221 (-0.016)	
>450	Topsoil	Urea	0.6 (-0.1)	- (0)	0.6 (0)	47 (-8)	86 (-8)	\$8,752 (-158)	0.379 (-0.031)	
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.8 (-0.2)	- (0)	0.8 (-0.1)	14 (-7)	53 (-7)	\$8,412 (-103)	0.240 (-0.024)	
	Sub-soil	Urea	1.5 (0)	3.1 (-0.1)	0.5 (-0.1)	46 (-8)	85 (-8)	\$8,527 (-189)	0.394 (-0.032)	
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	1.6 (-0.1)	3.2 (-0.2)	0.6 (-0.1)	12 (-8)	51 (-8)	\$8,183 (-134)	0.251 (-0.028)	
	Top and sub-soil	Urea	2.2 (0)	2.9 (-0.1)	0.5 (-0.1)	47 (-8)	86 (-8)	\$8,510 (-193)	0.399 (-0.032)	
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	2.3 (-0.1)	2.9 (-0.2)	0.7 (-0.1)	13 (-7)	52 (-7)	\$8,168 (-138)	0.259 (-0.027)	

\* This lime application is divided equally between the 10-20 cm and 20-30 cm soil horizons

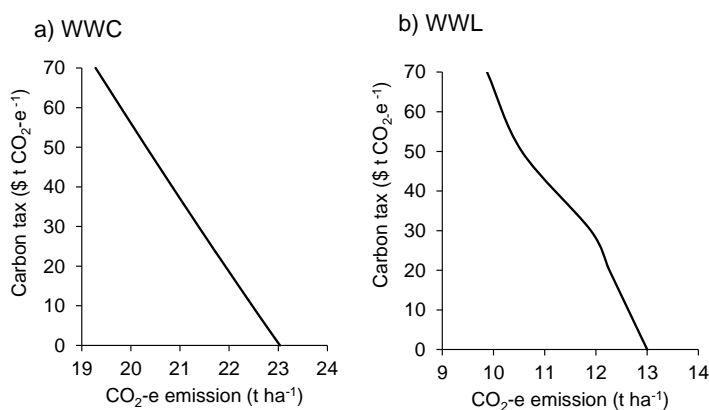


1 Figure 6 depicts the absolute change in NPV and CO<sub>2</sub>-e emissions when the carbon tax is  
 2 \$20 t CO<sub>2</sub>-e<sup>-1</sup> relative to when the carbon tax is zero for the WWC and WWL rotations. In  
 3 general, absolute reductions in both NPV and emissions are higher when rainfall is higher,  
 4 they are both higher for canola than for lupins (which has lower emissions due to less  
 5 nitrogen fertilizer being applied), and both are higher when nitrogen is applied as urea rather  
 6 than ammonium sulfate (because the former has higher emissions). There are no clear  
 7 trends with the acidity in different soil layers.



8  
 9 Figure 6. Absolute change in NPV and emissions when the carbon tax is \$20 t CO<sub>2</sub>-e<sup>-1</sup> relative to when the  
 10 carbon tax is zero for the WWL and WWC rotations. Results shown are for different nitrogen fertilizer types  
 11 and different rainfall zones with different soil acidity conditions under lime dissolution scenario 1 (IPCC  
 12 assumption) when liming method is surface plus sub-surface application.

13 The sensitivity of the GHG emissions to the tax rate is examined for different rotations by  
 14 varying the carbon tax within the range \$0 to 70 t CO<sub>2</sub>-e<sup>-1</sup> (see Figure 7). The emissions are  
 15 not highly responsive to tax changes. Increasing the tax from zero to \$70 t CO<sub>2</sub>-e<sup>-1</sup>, total  
 16 emissions over 80 years decrease from about 23 to 19 t ha<sup>-1</sup> in the WWC rotation and from  
 17 13 to 10 t ha<sup>-1</sup> in the WWL rotation. The price elasticity of emissions (the percentage change  
 18 in emissions relative to the percentage change in the carbon tax) is an average of -0.06 for  
 19 the WWC rotation and an average of -0.09 for WWL. Thus, in this farming system, emissions  
 20 are relatively unresponsive to carbon pricing.



21

22 Figure 7. Total emission responses to changes in carbon tax for the WWC and WWL rotations in the medium  
 23 rainfall (325-450 mm) zone with top and sub-soil acidity condition when nitrogen fertilizer is urea, liming method  
 24 is surface plus sub-surface application under lime dissolution scenario 1 (IPCC assumption).

25 We can explore the impact of carbon pricing on social welfare via its influence on lime and  
 26 nitrogen management, as illustrated in Figure 3. Table 4 shows the net social benefit of the  
 27 carbon tax for different rainfall zones and for different carbon taxes (where the social cost  
 28 of emissions is assumed to be equal to the carbon tax). For this context, and for these  
 29 practices, the impact of a carbon tax on farm profits would be small to modest, ranging from  
 30 a 3-4 percent reduction at a carbon tax of \$20 t CO<sub>2</sub>-e<sup>-1</sup> to 7-9 percent at a tax of \$50 t CO<sub>2</sub>-  
 31 e<sup>-1</sup>. This result is context-specific. We note that a variety of results have been obtained in

32 other studies of the effect of carbon pricing on the profitability of agriculture. For example,  
33 Tang et al. (2018) analyzed a mixed crop-livestock farming system in Western Australia and  
34 found that a A\$20 t CO<sub>2</sub>-e<sup>-1</sup> carbon tax would reduce emissions by 13.5 percent and farm  
35 profits by 4 percent. By contrast, Petersen et al. (2003) found that profits on a livestock-  
36 dominant farm in south-western Australia would be highly sensitive to a carbon tax, reflecting  
37 the relatively high emissions from livestock. Depending on the wool price, farm profits would  
38 fall to zero at a carbon price between A\$11 and A\$43 t CO<sub>2</sub>-e<sup>-1</sup>. Ozkan et al. (2012) found  
39 that profits for a dairy farm in the Australian state of Victoria would be reduced by around 6-  
40 7 percent (carbon tax A\$15 t CO<sub>2</sub>-e<sup>-1</sup>) or 10-11 percent (carbon tax A\$25 t CO<sub>2</sub>-e<sup>-1</sup>). At a  
41 more aggregated level, Bakam and Matthews (2009) showed that the cost of a carbon price  
42 to the agriculture sector depends on the degree of compliance with the policy, and on details  
43 of the design of the carbon pricing scheme. For a cap-and-trade scheme in Scotland, they  
44 found that farmers face reductions in gross margin of up to 50 percent for a 30 percent  
45 reduction in emissions. On the other hand, Peters et al. (2001) found that a carbon price of  
46 US\$14 t CO<sub>2</sub>-e<sup>-1</sup> would reduce U.S. farm profits in aggregate by only 0.02 percent, and even  
47 a charge of US\$100 would only reduce farm profit by 2.1 percent.

48 Interestingly, the net social benefits of the carbon tax calculated in this study are even  
49 smaller than the modest impact on farmers' profits: 76 to 97 percent as large. This is not to  
50 say that the tax does not have benefits overall; the reduction in externalities has benefits  
51 that are more than the reduction in farm profits (i.e., the net benefits are positive). However,  
52 the size of the net benefits are small. An additional benefit that is not captured in our model  
53 is the potential for a carbon tax to create an incentive for farmers to innovate in order to  
54 reduce the cost to them of the carbon tax. As well as benefiting the farmers, this would  
55 reduce the cost to society to achieve any particular emissions abatement target.

Table 4. The net social benefit of carbon pricing, the total emissions and NPV before and after carbon pricing (over 80 years) for different carbon taxes in different rainfall zones with top and sub-soil acidity condition for the WWC rotation when the nitrogen fertilizer is urea and liming method is surface plus sub-surface application under lime dissolution scenario 1 (IPCC assumption).

Annual rainfall (mm)	Carbon tax (\$ t CO <sub>2</sub> -e <sup>-1</sup> )	CO <sub>2</sub> -e emission before carbon pricing (t ha <sup>-1</sup> )	CO <sub>2</sub> -e emission after carbon pricing (t ha <sup>-1</sup> )	NPV before carbon pricing (\$ ha <sup>-1</sup> )	NPV after carbon pricing (\$ ha <sup>-1</sup> )	Decline in NPV (\$ ha <sup>-1</sup> )	Net social benefit of carbon pricing (\$ ha <sup>-1</sup> )
<325	20	16.2	15.7	6,310	6,126	184	140
	30	16.2	14.9	6,310	6,037	273	213
	50	16.2	14.4	6,310	5,867	443	368
325-450	20	23.0	21.9	7,002	6,752	250	210
	30	23.0	21.4	7,002	6,630	372	319
	50	23.0	20.3	7,002	6,397	605	546
>450	20	30.6	28.7	8,181	7,857	324	287
	30	30.6	27.8	8,181	7,701	480	438
	50	30.6	26.0	8,181	7,405	776	752

56 Realistically, given the fact that the modeled carbon tax has a small-to-modest impact on  
 57 farm profits, its capacity to generate incentives to innovate would also be small.

58 The Supplementary Information shows results in which we change the assumption  
 59 regarding the dissolution of lime in the soil from the standard IPCC assumption (that it all  
 60 dissolves in the year of application) to the more realistic assumption used in the Optlime  
 61 model (that lime dissolves over a number of years, depending on physical conditions in the  
 62 soil). The results suggest that lime application rates, total emissions, and NPV are all  
 63 relatively insensitive to what is assumed about the lime dissolution rate (see Figure S11 and  
 64 Table S11 and S12 of the Supplementary Information).

65 The study has implications for agencies responsible for agricultural policy and agricultural  
 66 extension. It shows how decisions about nitrogen fertilizer and liming would be jointly  
 67 affected by the imposition of a carbon tax. Extension advice that provides specific  
 68 recommendations about economically optimal rates should be stated conditionally on  
 69 variables such as average rainfall, initial acidity condition, fertilizer type, and, if relevant, the

70 level of carbon tax. In relation to climate policy, the study shows that the response of these  
71 grain farmers to a carbon price, in terms of reducing their emissions, would not be large.  
72 Once transaction costs of such a scheme were accounted for, it may not be worth the cost  
73 of imposing a carbon tax on these farmers, depending on judgements about the social cost  
74 of carbon emissions.

#### 75 **4. Conclusion**

76 There is a complex interplay between soil acidity, nitrogen fertility, and GHG emissions in  
77 farming systems with acidity-prone soils. In our case study, in the northern part of the  
78 Western Australian wheatbelt, both lime and nitrogen applications emit GHGs that would  
79 increase a farmer's liability to pay a carbon tax if such a scheme was applied to agriculture.  
80 Higher rates of nitrogen application result in increased soil acidification, in turn causing  
81 higher optimal rates of lime application to counter that acidity. Other nitrogen related  
82 decisions, such as the type of nitrogen fertilizer and the crop rotation, also affect soil  
83 acidification, lime rates, and emissions. In our example, incorporating the legume crop lupin  
84 reduces CO<sub>2</sub>-e emissions by about 50 percent. Input rates, acidification, and emissions are  
85 also affected by the level of rainfall and by which soil layers are acidic.

86 Imposition of a tax on carbon emissions would reduce the optimal application rates for  
87 nitrogen fertilizer and lime, but the reductions in emissions from the farming system in our  
88 case study would be modest. For example, if the carbon tax is \$20 t CO<sub>2</sub>-e<sup>-1</sup>, emissions are  
89 reduced by between 4 and 10 percent, depending on the context (rainfall, fertilizer type,  
90 etc.). If a carbon tax of \$20 t CO<sub>2</sub>-e<sup>-1</sup> was applied to crop production in this region, the effect  
91 on farm profits would be modest, with a reduction of 3 to 4 percent. Importantly, the net

92 social benefits of a carbon tax (the benefit from reduced externalities minus the deadweight  
93 loss from reduced crop production) would be even less than the private costs to farmers.

94 This study has a number of limitations. Firstly, for reasons of model tractability, we did not  
95 represent year-to-year climatic variability or stochastic prices in the dynamic model.  
96 Secondly, our representation of an emissions tax on broadacre dryland farming is relatively  
97 simple and does not include transaction costs to the farmers or to the government. We have  
98 not attempted to explore how an emissions tax system could be designed and implemented  
99 most efficiently. Thirdly, we did not model the effects of nitrogen fertilizer on crop quality,  
100 particularly the grain protein level in wheat grain. Thus our model slightly underestimates  
101 the economic effect of reducing nitrogen fertilizer rates. These are all topics for which further  
102 research may be beneficial.

## 103 **5. Acknowledgements**

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## 311 **Supplementary Information**

### 312 **1. Pre-farm CO<sub>2</sub>-e emissions**

#### 313 **1.1. Lime production and transport**

314 The emissions from lime production and transportation (kg CO<sub>2</sub>-e ha<sup>-1</sup>) in a given year  $t$ ,  
315  $L_{PT_t}$ , are calculated as:

$$316 \quad L_{PT_t} = (0.017 \times 1000 \times \sum_{i=1}^3 L_{t,i}) + (d_1 \times q_1 \times \sum_{i=1}^3 L_{t,i}) \quad (\text{SI1})$$

317 where the multiplier 0.017 represents the emissions from the production (quarrying and  
318 screening) of lime (kg CO<sub>2</sub>-e kg lime<sup>-1</sup>) (Barton et al. 2014); the 1000 multiplier converts lime  
319 application rate from t to kg;  $L_{t,i}$  is the lime rate applied in a given year  $t$  and to a given soil  
320 horizon  $i$  (0-10 cm, 10-20 cm and 20-30 cm) (t ha<sup>-1</sup>);  $d_1$  is the average distance for the lime  
321 freight from the lime source to the quarry, which is assumed to be 100 km;  $q_1$  is the  
322 emissions from transporting lime by a 50 tonne truck, set at 0.236 (kg CO<sub>2</sub>-e t lime<sup>-1</sup> km<sup>-1</sup>)  
323 (T. Grant pers. comms.).

#### 324 **1.2. Nitrogen fertilizer production and transport**

325 The emissions from nitrogen fertilizer production and transportation (kg CO<sub>2</sub>-e ha<sup>-1</sup>) in a  
326 given year  $t$ ,  $N_{PT_t}$ , are calculated as:

$$327 \quad N_{PT_t} = (a \times N_t) + (d_n \times q_n \times N_t/1000) \quad (\text{SI2})$$

328 where  $a$  represents the emissions from the production of nitrogen fertilizer (kg CO<sub>2</sub>-e kg  
329 fertilizer<sup>-1</sup>), set at 0.863 for urea and 0.416 for ammonium sulfate (Cowie and Cowie  
330 2013);  $N_t$  is the nitrogen fertilizer rate applied in year  $t$  (kg of fertilizer product ha<sup>-1</sup>);  $d_n$

331 represents the distance that nitrogen fertilizer is freighted from the fertilizer works to the  
332 farm, which is assumed to be 475 km;  $q_n$  is the emissions from transporting by a 50 tonne  
333 truck, set at 0.236 (kg CO<sub>2</sub>-e t fertilizer<sup>-1</sup> km<sup>-1</sup>) (T. Grant pers. comms.); The divisor 1000  
334 converts nitrogen fertilizer from kg to t. These emissions are zero for lupin years.

### 335 **1.3. Diesel production and transport**

336 The emissions from diesel production and transportation (kg CO<sub>2</sub>-e ha<sup>-1</sup>) in a given year  $t$ ,  
337  $D_{PT_t}$ , are calculated as:

$$338 \quad D_{PT_t} = D_{on_t} / 2.7 \times F_D \quad (SI3)$$

339 where  $D_{on_t}$  are the emissions from on-farm diesel use in a given year (kg CO<sub>2</sub>-e ha<sup>-1</sup>); the  
340 multiplier 2.7 converts  $D_{on_t}$  from kg CO<sub>2</sub>-e ha<sup>-1</sup> to ltr diesel ha<sup>-1</sup>;  $F_D$  is the Scope 3 NGA  
341 emission factor (Department of Climate Change and Energy Efficiency 2010) representing  
342 indirect emissions from the extraction, production and transportation of diesel fuel, set at 0.2  
343 (kg CO<sub>2</sub>-e ltr<sup>-1</sup>).

## 344 **2. On-farm CO<sub>2</sub>-e emissions**

345 Unless otherwise stated, on-farm emissions are estimated following the methodology used  
346 to inventory and report Australia's emissions in accordance with the United Nations  
347 Framework Convention on Climate Change (Department of the Environment and Energy  
348 2018). Note that none of the emissions associated with nitrogen fertilizer use occur when  
349 lupin are grown as it is a legume crop and so has no nitrogen fertilizer applied to it.

### 350 **2.1. Direct N<sub>2</sub>O emissions from nitrogen fertilizer**

351 The direct N<sub>2</sub>O emissions from nitrogen fertilizer application in a given year  $t$  (kg CO<sub>2</sub>-e ha<sup>-1</sup>),  $N_{DR_t}$ , are calculated as:

$$353 \quad N_{DR_t} = N_{f_t} \times F_n \times 1.571 \times 298 \quad (SI4)$$

354 where  $N_{f_t}$  is the elemental nitrogen (kg N ha<sup>-1</sup>) applied as either urea or ammonium fertilizer  
355 in a given year;  $F_n$  is the emission factor for the fraction of nitrogen fertilizer that is emitted  
356 as N<sub>2</sub>O, set at 0.002; the multiplier 1.571 is the standard conversion factor to convert of the  
357 elemental mass of nitrogen to the molecular mass of N<sub>2</sub>O; and the multiplier 298 is the global  
358 warming potential of N<sub>2</sub>O over 100 years, which converts the N<sub>2</sub>O emissions to CO<sub>2</sub>-e.

## 359 **2.2. Direct N<sub>2</sub>O emissions from crop residues**

360 As crop residues decompose the nitrogen they contain can be emitted as N<sub>2</sub>O. In a given  
361 year  $t$  these emissions  $R_{cr_t}$  (kg CO<sub>2</sub>-e ha<sup>-1</sup>) are calculated as:

$$362 \quad R_{cr_t} = [(Y_t \times G_h \times (1 - G_A - G_r) \times M \times N_A) + (Y_t \times G_h \times G_{AB} \times M \times N_B)] \times F_R \times \\ 363 \quad 1.571 \times 298 \quad (SI5)$$

364 where  $Y_t$  is the yield of the crop grown in a given year (kg ha<sup>-1</sup>);  $G_h$  is the ratio of above-  
365 ground crop residue to the harvested grain (kg residue kg grain<sup>-1</sup>), set at 1.5 for wheat, 2.1  
366 for canola and 1.37 for lupin;  $G_A$  is the fraction of above-ground crop residue that is burnt,  
367 set at 0.06 and  $G_r$  is the fraction of above-ground crop residue that is typically removed, set  
368 at 0.11 for the Western Australian Wheatbelt area where conservation agriculture is  
369 commonly practiced (Department of the Environment and Energy 2018);  $M$  is the dry matter  
370 content (kg dry weight kg residue<sup>-1</sup>), set at 0.88 for wheat, 0.96 for canola and 0.87 for lupin;  
371  $N_A$  is the nitrogen content of above-ground residues (kg N kg residue<sup>-1</sup>), set at 0.006 for  
372 wheat and 0.009 for both canola and lupin;  $G_{AB}$  is the ratio of below-ground crop residue to

373 above-ground residue, set at 0.29, 0.33 and 0.51 for wheat, canola and lupin respectively;  
 374  $N_B$  is the nitrogen content of below-ground residues, set at 0.01 for all crops;  $F_R$  is the IPCC  
 375 emission factor for the fraction of nitrogen in residues that is emitted as  $N_2O$ , set at 0.01; the  
 376 multiplier 1.571 is the molecular conversion factor and the multiplier 298 is the global  
 377 warming potential used to convert  $N_2O$  emissions into  $CO_2$ -e.

### 378 **2.3. Indirect $N_2O$ emissions from N fertilizer**

379 The indirect  $N_2O$  emissions from nitrogen fertilizer applied in a given year  $t$  ( $kg\ CO_2$ -e  $ha^{-1}$ ),  
 380  $N_{IDR_t}$ , are calculated as:

$$381 \quad N_{IDR_t} = N_{IDRV_t} + N_{IDRF_t} + N_{IDRR_t} \quad (SI6)$$

382 where  $N_{IDRV_t}$  is the indirect  $N_2O$  emissions from  $NH_3$  volatilization in a given year  $t$  ( $kg\ CO_2$ -  
 383 e  $ha^{-1}$ ). It is the fraction of nitrogen applied as fertilizer that volatilizes into the atmosphere as  
 384  $NH_3$  and is subsequently emitted as  $N_2O$  while depositing back to the land.  $N_{IDRF_t}$  is the  
 385 indirect  $N_2O$  emissions from the leaching and run-off of nitrogen from nitrogen fertilizer in a  
 386 given year  $t$  ( $kg\ CO_2$ -e  $ha^{-1}$ ).  $N_{IDRR_t}$  is the indirect  $N_2O$  emissions from the leaching of  
 387 nitrogen contained in crop residues in a given year  $t$  ( $kg\ CO_2$ -e  $ha^{-1}$ )<sup>3</sup>.

388 The indirect  $N_2O$  emissions  $N_{IDRV_t}$  are calculated as:

$$389 \quad N_{IDRV_t} = N_{f_t} \times 0.1 \times F_n \times 1.571 \times 298 \quad (SI7)$$

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<sup>3</sup>  $N_2O$  can also be emitted indirectly from the leaching of N that has mineralised from soil carbon Department of the Environment and Energy (2018). National Inventory Report 2016 Vol 1, Commonwealth of Australia, Canberra.. However, these emissions are omitted on the basis that they would not necessarily differ between the different rotations, lime and fertilizer strategies analyzed in this study.



390 where the multiplier 0.1 represents the proportion of applied nitrogen that volatilizes as NH<sub>3</sub>  
391 (IPCC 2006).

392 The indirect N<sub>2</sub>O emissions  $N_{IDRF_t}$  are calculated as:

$$393 \quad N_{IDRF_t} = N_{f_t} \times 0.223 \times 0.3 \times F_{lr} \times 1.571 \times 298 \quad (SI8)$$

394 where the multiplier 0.223 represents the proportion of the nitrogen available for leaching  
395 and runoff and the multiplier 0.3 is the IPCC default value for the fraction of available  
396 nitrogen that is actually lost through leaching and runoff;  $F_{lr}$  is the IPCC emission factor for  
397 the fraction of leached nitrogen that is emitted as N<sub>2</sub>O, set at 0.0075.

398 The indirect N<sub>2</sub>O emissions  $N_{IDRR_t}$  are calculated as:

$$399 \quad N_{IDRR_t} = [(Y_t \times G_h \times (1 - G_A - G_r) \times M \times N_A) + (Y_t \times G_h \times G_{AB} \times M \times N_B)] \times \\ 400 \quad 0.223 \times 0.3 \times F_1 \times 1.571 \times 298 \quad (SI9)$$

#### 401 **2.4. Burning crop residues**

402 The emissions from burning crop residues in a given year  $t$  (kg CO<sub>2</sub>-e ha<sup>-1</sup>),  $B_{cr_t}$ , are  
403 calculated as:

$$404 \quad B_{cr_t} = B_{crn_t} + B_{crc_t} \quad (SI10)$$

405 where  $B_{crn_t}$  and  $B_{crc_t}$  are the N<sub>2</sub>O and CH<sub>4</sub> emissions emitted from the combustion of crop  
406 residues in a given year  $t$  (kg CO<sub>2</sub>-e ha<sup>-1</sup>). Note: the CO<sub>2</sub> emitted by burning crop residues  
407 is not counted as these emissions are equal to the CO<sub>2</sub> that the growing crop removed from  
408 the atmosphere.

409 The emissions  $B_{crn_t}$  are calculated as:

410 
$$B_{\text{crn}_t} = 0.0076 \times N_A \times TM_t \times 1.571 \times 298 \quad (\text{SI11})$$

411 where the multiplier 0.0076 represents the emission factor for the fraction of nitrogen in the  
412 residue that is emitted as N<sub>2</sub>O.  $TM_t$  is the total mass of crop residue assumed to be burnt  
413 in Western Australian cropping systems in a given year  $t$  (kg ha<sup>-1</sup>), calculated as:

414 
$$TM_t = Y_t \times G_h \times 0.5 \times M \times 0.94 \times G_A \quad (\text{SI12})$$

415 where the multiplier 0.5 is the fraction of above-ground crop residue remaining at the time  
416 of burning and the multiplier 0.94 is the burning efficiency.

417 The emissions  $B_{\text{crc}_t}$  are calculated as:

418 
$$B_{\text{crc}_t} = TM_t \times C_r \times 0.0035 \times 1.33 \times 25 \quad (\text{SI13})$$

419 where  $C_r$  is the fraction of the crop residue that is carbon, set at 0.4 for all crops. The  
420 multiplier 0.0035 represents the emission factor for the fraction of this carbon emitted as  
421 CH<sub>4</sub>. The multiplier 1.33 is the standard conversion factor to convert the elemental mass of  
422 carbon to the molecular mass of CH<sub>4</sub>. The multiplier 25 is the IPCC AR4 global warming  
423 potential of CH<sub>4</sub> over 100 years, and converts CH<sub>4</sub> emissions to CO<sub>2</sub>-e.

## 424 **2.5. Urea hydrolysis**

425 When urea (CO(NH<sub>2</sub>)<sub>2</sub>) dissolves in soil, carbon contained in the urea is released as CO<sub>2</sub>.  
426 Emissions from urea hydrolysis in a given year  $t$  (kg CO<sub>2</sub>-e ha<sup>-1</sup>),  $U_{h_t}$ , are calculated as:

427 
$$U_{h_t} = N_t \times 0.2 \times 3.667 \quad (\text{SI14})$$

428 where  $N_t$  is the amount of urea applied in a given year (kg ha<sup>-1</sup>); the multiplier 0.2 is the  
429 emission factor for proportion of carbon in urea; and the multiplier 3.667 converts the

430 elemental mass of carbon to the molecular mass of CO<sub>2</sub>. Urea hydrolysis does not occur  
431 with ammonium sulfate fertilizer (nor with lupin crops).

## 432 **2.6. Diesel use**

433 The emissions from on-farm diesel use represent the emissions from lime and nitrogen  
434 fertilizer application. Diesel consumption for these tasks is appraised as:

- 435 • Lime applications to the soil surface were assumed to use 0.37L of diesel per tonne  
436 of lime applied per ha, based on Barton et al. (2014).
- 437 • Sub-surface lime placement involves ripping the soil profile and then injecting  
438 bands of lime at depth. Fuel use is therefore estimated at 6.9L per ha for ripping  
439 (Davies and Johnston 2012) plus 0.37L of diesel per tonne per ha of lime applied to  
440 the subsoil.
- 441 • Fertilizer application was assumed to use 0.81L per ha (Biswas et al. 2010). For the  
442 sake of simplicity, this was assumed for all application rates (unlike lime which  
443 tends to be applied at rates measured in tonnes, fertilizer is applied at much lower  
444 rates, meaning changes in these rates does not have a large bearing on the fuel  
445 used to apply fertilizer).

446 Therefore formally, emissions from on-farm diesel use in a given year (kg CO<sub>2</sub>-e ha<sup>-1</sup>),

447  $D_{on_t}$ , are calculated as:

448

$$449 \quad D_{on_t} = [(0.37 \times \sum_{i=1}^3 L_{t,i}) + (\text{if } \sum_{i=2}^3 L_{t,i} > 0 \text{ then } 6.9) + (\text{if } N_{f_t} > 0 \text{ then } 0.81)] \times 2.7$$

450

(SI15)

451 where  $L_{t,i}$  is the lime rate applied in a given year for soil horizons 0-10 cm, 10-20 cm, and  
452 20-30 cm ( $\text{t ha}^{-1}$ ) in a given year  $t$ , and the multiplier 2.7 is the emission factor for the  $\text{CO}_2$ -  
453 e produced per litre of diesel used (Department of Climate Change and Energy Efficiency  
454 2010).

### 455 **2.7. Lime dissolution**

456 Lime produces  $\text{CO}_2$  while dissolving in wet soil. In estimating these emissions from lime  
457 dissolution two scenarios were tested.

## 458 **3. Scenario 1 (IPCC assumption)**

459 Following Tier 1 IPCC emissions methodologies (IPCC 2006), lime dissolution and the  
460 associated emissions are assumed to occur entirely in the year of application. In which case  
461 the emissions from lime dissolution in a given year  $t$  ( $\text{kg CO}_2\text{-e ha}^{-1}$ ),  $L_{d,t}$ , are calculated as:

$$462 \quad L_{d,t} = 1000 \times \sum_{i=1}^3 L_{t,i} \times \lambda \times F_L \times 3.667 \quad (\text{SI16})$$

463 where the multiplier 1000 converts lime application rates from  $\text{t ha}^{-1}$  to  $\text{kg ha}^{-1}$ ;  $\lambda$  is the total  
464 neutralising value of the lime that converts the applied lime rate to pure  $\text{CaCO}_3$ , set at 0.893  
465 based on the most common lime type in the study area;  $F_L$  is the emission factor for  
466 limestone, set at 0.12; and the multiplier 3.667 converts the elemental mass of carbon to the  
467 molecular mass of  $\text{CO}_2$

## 468 **4. Scenario 2 (Optlime assumption)**

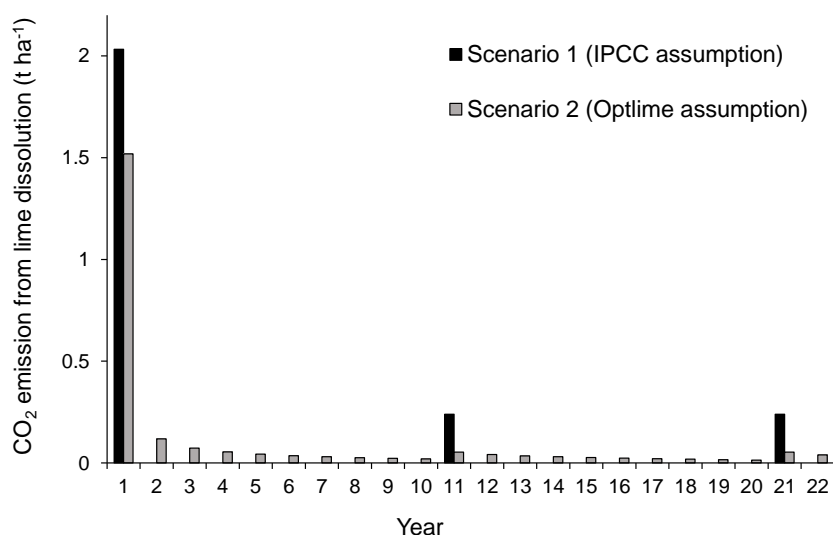
469 In reality, lime does not completely dissolve in the year of application, especially in the  
470 conditions of the study area (Gazey 2008; Whitten et al. 2000). The protracted nature of the  
471 lime dissolution process results in dissolution of lime for many subsequent years, even in

472 the absence of further applications. As lime dissolution is one of the key processes captured  
 473 in the Optlime model, the emissions can therefore be predicted based on the rate of lime  
 474 dissolution endogenously calculated in the model. In this scenario Equation (SI16) is  
 475 adjusted, becoming:

$$476 \quad L_{d_t} = 1000 \times (\sum_{i=1}^3 \sum_{m=1}^{12} r_{t,m,i}^\phi) \times F_L \times 3.667 \quad (\text{SI17})$$

477 where  $r_{t,m,i}^\phi$  is the net rate of lime dissolution in the given year  $t$ , month  $m$ , and soil horizon  
 478  $i$ , as calculated endogenously in the model. This rate depends on a number of interacting  
 479 factors such as lime particle size, rainfall, and soil pH.

480 Changing the lime dissolution scenario from IPCC assumption to Optlime assumption  
 481 affects the lime dissolution rates between the liming intervals (Figure SI1). However, lime  
 482 and nitrogen application rates are almost unresponsive to this change. The response of NPV  
 483 and emissions to this change is also less than one percent (Table SI1 and SI2).



484  
 485 Figure SI1. Emission from lime dissolution under different lime dissolution scenarios for the WWC rotation in  
 486 medium rainfall (325-450 mm) zone with top and sub-soil acidity condition when nitrogen fertilizer is urea,  
 487 liming method is surface plus sub-surface application and the carbon price is zero

Table SI1. Lime application and nitrogen fertilizer rates, NPV and emissions under lime dissolution scenario 2 (Optlime assumption). The numbers in parentheses show changes relative to lime dissolution scenario 1 (IPCC assumption). Results shown are for the WWC rotation in medium annual rainfall zone (325-450 mm) with different soil acidity conditions when the carbon price is set to \$20 t CO<sub>2</sub>-e<sup>-1</sup>.

Acidity condition	Nitrogen fertilizer	Lime application rate (t ha <sup>-1</sup> )			Nitrogen fertilizer rate (kg N ha <sup>-1</sup> )		NPV (\$ ha <sup>-1</sup> )	Average CO <sub>2</sub> -e emission (t ha <sup>-1</sup> yr <sup>-1</sup> )
		Surface (year 1)	Sub-surface* (year 1)	Surface maintenance (10 yearly)	Wheat	Canola		
Topsoil	Urea	1.0 (0)	- (0)	0.6 (0)	78 (0)	79 (0)	\$6,980 (1)	0.530 (0)
	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	2.3 (0)	- (0)	1.4 (0)	58 (0)	59 (0)	\$6,291 (6)	0.387 (0)
Sub-soil	Urea	1.7 (0.1)	3.1 (-0.1)	0.5 (0)	77 (0)	79 (0)	\$6,773 (7)	0.543 (0)
	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	3.3 (0.2)	3.6 (-0.1)	1.3 (0)	57 (1)	58 (1)	\$6,056 (17)	0.398 (0)
Top and sub-soil	Urea	2.3 (0)	2.8 (0)	0.6 (0)	77 (0)	79 (0)	\$6,755 (3)	0.549 (0)
	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	3.3 (0.1)	3.3 (0)	1.3 (0)	58 (0)	59 (0)	\$6,055 (8)	0.407 (0)

\* This lime application is divided equally between the 10-20 cm and 20-30 cm soil horizons

Table SI2. Lime application and nitrogen fertilizer rates, NPV and emissions under lime dissolution scenario 2 (Optlime assumption). The numbers in parentheses show changes relative to lime dissolution scenario 1 (IPCC assumption). Results shown are for the WWL rotation in medium annual rainfall zone (325-450 mm) with different soil acidity conditions when the carbon price is set to \$20 t CO<sub>2</sub>-e<sup>-1</sup>.

Acidity condition	Nitrogen fertilizer	Lime application rate (t ha <sup>-1</sup> )			Nitrogen fertilizer rate (kg N ha <sup>-1</sup> )		NPV (\$ ha <sup>-1</sup> )	Average CO <sub>2</sub> -e emission (t ha <sup>-1</sup> yr <sup>-1</sup> )
		Surface (year 1)	Sub-surface* (year 1)	Surface maintenance (10 yearly)	Wheat after lupin	Wheat after wheat		
Topsoil	Urea	0.5 (0)	- (0)	0.4 (0)	33 (0)	63 (0)	\$7,474 (0)	0.288 (0)
	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.6 (0)	- (0)	0.7 (0)	13 (0)	43 (0)	\$7,214 (1)	0.204 (0)
Sub-soil	Urea	1.3 (0.1)	2.8 (0)	0.3 (0)	32 (0)	62 (0)	\$7,263 (4)	0.302 (0)
	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	1.7 (0.1)	2.9 (-0.1)	0.5 (0)	12 (0)	42 (1)	\$6,995 (6)	0.215 (0)
Top and sub-soil	Urea	1.9 (0)	2.6 (0)	0.4 (0)	33 (0)	62 (0)	\$7,245 (2)	0.307 (0)
	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	2.2 (0)	2.7 (0)	0.5 (0)	13 (0)	43 (0)	\$6,980 (3)	0.222 (0)

\* This lime application is divided equally between the 10-20 cm and 20-30 cm soil horizons

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