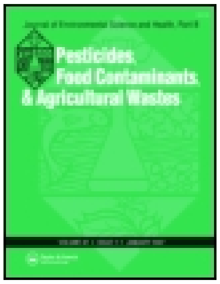

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An assessment of greenhouse gas emissions from the Australian vegetables industry

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Recently, partly due to the increasing carbon consciousness in the electorates and partly due to the imminent introduction of the Australian Government's Carbon Pollution Reduction Scheme (CPRS), estimating carbon footprints is becoming increasingly necessary in agriculture. By taking data from several sources, this study estimates the national greenhouse gas (GHG) emissions from a variety of farm inputs, for the 23 key vegetables crops grown in Australia. For the 121,122 ha of land occupied by vegetable farms, there are 1.1 $MtCO_2e$ GHG emissions or 9.2 tCO_2e ha^{-1}. In total, 65 % of total GHG emissions from the vegetable industry are due to electricity use for irrigation and post-harvest on-farm activities, 17 % from soil N_2O emissions due to N fertiliser use, 10 % from agrochemicals, 7 % through fossils fuels and 1 % from on-farm machinery. The top four vegetables (by area), potatoes, lettuce, tomatoes and broccoli account for 29.1 %, 7.9 %, 5.9 % and 7.2 % of total GHG emissions from vegetables, respectively. However, the ratio of GHG emissions between the highest and lowest-emitting crops per hectare and per tonne, are different. Therefore, care must be exercised in carbon footprint labelling vegetable products to ensure that the labels reflect carbon emissions on a per tonnage basis.

Keywords: Vegetable industry; carbon pollution reduction scheme; greenhouse gas emissions; agrochemicals; electricity; machinery; fuels.

Introduction

The vegetable industry in Australia contributed 6 % of the gross value of agricultural production in the period 1999–2000 to 2003–04.[1] Gross value of vegetable production in Australia rose by 3.8 % from $3.10 billion in 2006-07 to $3.22 billion in 2007-2008.[2]During the same time, the gross value of exports decreased by 6.34 % (from $410 million to $384 million) whilst imports increased by 17.87 % (from $621 million to $732 million), mainly from China.[1–2]

Vegetables are labour–, water– and energy– intensive crops. Vegetable production requires various forms of energy, whether for ploughing, applying agrochemicals (fertilizers, herbicides, insecticides and fungicides), planting, irrigating, crop cultivation, harvesting, refrigeration, food processing, or transport.[3] The increase in labour costs and the increased need for agrochemicals and water resources in the mid 20th century necessitated the invention of new irrigation techniques and farm machinery resulting in the intensive and mechanized modern vegetable cultivation system of today. However, intensification, mechanisation and modernisation in agriculture have never been greenhouse gas (GHG) emissions-free, as they demand more fuel, farm machinery and agrochemicals. In addition, production, packaging, and transportation require significant energy resources, resulting in even more GHG emissions.[4–8] Therefore, although vegetable farms only occupy 0.034 % of available agricultural land in Australia, it accounts for >1 % of agricultural GHG emissions.[9]

In Australia, agriculture is the second largest source of GHG's behind stationary energy whilst it is the dominant source of methane (CH_4; 59 % of national emissions) and nitrous oxide (N_2O; 83.9 % of national emissions).[10] Agriculture produced 86,831 $GgCO_2e$ GHG emissions in 1990, which was about 15.7 % of net national emissions. In 2006, GHG emissions from agriculture increased to 90,112 $GgCO_2e$, representing 15.6 % of net national emissions.[10] Although the percentage share of agricultural emissions

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to net national emissions was similar in 1990 and 2006, emissions from agriculture during this period increased by 3.8 %, and are directly attributed to rising farm inputs.[11] For example, between 1987 and 2000, nitrogen (N) fertiliser use increased by 325 %.[9] Given that >50 % of applied N is either lost through leaching into the soil or released into the atmosphere as N_2O[12] which has 298 times more global warming potential than CO_2,[13] N represents a major contributor of farm-based GHG emissions. Similarly, increasing farm machinery usage is another source of GHGs[4] with 51 % expended in farm machinery manufacture and 45 % in the production of chemical fertiliser.[14] However, GHG emissions due to production, packaging, storage, transportation and use of many farm inputs have been largely ignored in the literature.[15]

Due to the increasing carbon (C) consciousness of consumers and with the imminent introduction of the Australian Government's Carbon Pollution Reduction Scheme (CPRS),[16] a comprehensive study that accounts for all farm emissions from farming inputs for each economically significant vegetable crop grown is very much necessary. The aim of this study is to estimate GHG emissions from farming inputs for 23 vegetable crops grown in Australia. The specific objectives being to estimate GHG emissions: (1) from the production, packaging and transportation of agrochemicals; (2) of N_2O from soils due to the use of N-based fertilisers; (3) due to the extraction, production and use of electricity for irrigation; (4) due to extraction, production and use of electricity for cooling, refrigeration, cleaning and packaging vegetables; (5) from farm production and combustion of fossil fuels use; and (6) due to the production of farm machinery used for the vegetable industry.

The carbon pollution reduction scheme (CPRS) and the agricultural sector

The Australian Government plans to implement its comprehensive range of climate strategies, which includes mitigation, adaptation, and helping global communities to seek global solutions.[16] As a mitigation strategy, the Australian Government is committed to reducing Australia's GHG emissions by 5–15 % by 2020 and 60 % by 2050 at below 2000 levels.[16] To cost-effectively meet this target, the Australian Government's White Paper proposed a comprehensive CPRS, (scheduled for implementation in 2010) that will bring about 1,000 Australian companies (out of 7.6 million registered companies) that produce >25,000 $tCO_2e\ yr^{-1}$, under the CPRS.[16]

The CPRS is very comprehensive in terms of the number of GHGs being considered, the degree of sectoral coverage and the percentage of total national GHG coverage. The CPRS proposes to include all six major GHGs recognised by the Kyoto Protocol (these include: carbon dioxide (CO_2); nitrous oxide (N_2O); methane; sulphur hexafluoride; hydrofluorocarbon; perflurocarbon). The CPRS is more comprehensive than the EU's emissions trading scheme (EUETS)—the world's largest carbon market—which only included CO_2 in the first phase (2005–2007), and CO_2 and N_2O in the second phase (2008–2012).[17]

The CPRS covers all sectors except agriculture, with the decision whether to include agriculture under the CPRS by 2015, being made in 2013. By comparison, the EUETS does not cover both the forestry and agricultural sectors. Similarly, the New Zealand ETS, which included forestry in 2008, was supposed to include all other sectors (i.e., liquid fossil fuels in 2011, and agriculture, synthetic gases and waste in 2013) and all six GHGs in a stepwise manner[18], is currently being reviewed by the New Zealand Government. Also, the CPRS covers >75 % of Australian GHG emissions whereas the EUETS covers only 50 % of EU GHG emissions.[16,18]

Incorporating the agricultural sector in any domestic emissions trading scheme such as the CPRS is a contentious issue due to several unique features of the agricultural sector.[18–22] These include the spatially distributed nature of agriculture, the difficulty in measuring small changes in annual fluxes over wide areas, the non-permanence and reversibility of agriculture, and also the high transaction and administration costs and leakages.[23–25]

From 1990 to 2005, Annex I countries collectively decreased their agricultural emissions by 10 %[26] whilst Australia's emissions from agriculture increased by 3.8 %[9–10] to 15.6 % of Australia's GHG emissions[10]; this rises to 23 % when agricultural energy and transport inputs are included.[27] This figure is significantly higher than corresponding values for the agricultural sectors in central and Eastern Europe (3 %), former Soviet Union (3 %) and the United States (USA) (5.5 %).[21,26] If emissions from agriculture are left unchecked, they are likely to increase dramatically in the future and thus by not including agriculture in the CPRS, would make it difficult for the Australian Government to meet its GHG emissions reduction target for 2050.

Methods

Several international studies have quantified farm energy consumption for various farm inputs and activities.[14,28–30] However, the energy use data presented in these studies are in such diverse formats [i.e., volume (gallons or litres) of diesel, weight (kg, Mg) of coal, calories (kcal, Mcal), joules (MJ, GJ) and other units of energy (BTU) and energy or electricity (kWh)] making it extremely difficult to compare GHG emissions from different farming practices.[31] To help address this issue, this study will present all GHG emissions data as carbon dioxide equivalent (CO_2e).

Despite the Kyoto Protocol covering six of the major GHGs, only three (CO_2, N_2O and CH_4) are relevant to the vegetable industry and are addressed in this study. Although there are some SF_6 emissions in electric transmissions and chlorofluorocarbon (CFC) emissions in refrigeration, these are almost negligible and are therefore not considered in this study. A conversion factor was also used for N_2O (1t N_2O =298 tCO_2e) and for CH_4 (1 t CH_4 = 25 tCO_2e).[13] In order to assess the GHG emissions for all 23 vegetable crops and their associated farming operations, this study utilised a national dataset as presented in Rab et al.[32] Where national level data are not available, data from the New South Wales (NSW) vegetable industry was used and then extrapolated to the national level data as suggested by Rab et al.[32]

GHG emissions from the production, packaging, storage, and transportation of agrochemicals

Vegetables have been farmed in Australia since the beginning of European settlement and given the generally infertile nature of Australian soils, N fertilisers have been heavily relied upon through time to increase productivity. Relative to other fertilisers such as P and K, N requires more energy for its production.[6,14] Furthermore, vegetable crops require considerable protection from diseases and pests and thus more energy is required in the packaging, storage and transportation of agrochemicals (which includes insecticides, herbicides and fungicides) on a per unit basis than any other agricultural input[14,30] Hence, an increase in agrochemical inputs will result in an increase in GHG emissions in the production chain.

There are three common procedures (explained in more detail below) for estimating GHG emissions from agrochemical inputs: 1) estimating the amount of energy used in all processes of production, packaging, storage and transportation, and then estimating the subsequent GHG emissions; 2) estimating the global warming impact (GWI) of each agrochemical; and 3) estimating the amounts of fertiliser-element in each fertiliser and the amounts of active ingredients and then estimating GHG emissions.

1) Several studies have estimated the energy characteristics of agrochemical production. The Government of the State of Sao Paulo[30] estimated the amount of energy required in producing different agrochemicals in Brazil; Mudahar and Hignett[28] estimated the energy requirement for production, packing, transportation and application of fertilizers; and Shapouri et al.[33] calculated the energy required in the production of fertilizers and pesticides in the United States. However, estimates of net GHG emissions from all these studies are problematic. Chemical reactions are exothermic as they release energy, however none of these studies documented how much energy was released during these reactions. Although total energy calculations do provide clues about the relative GHG emissions from different agrochemicals, it is hard to determine the exact amount of external energy needed during the agrochemical production process. Consequently, this method was not used in this study.

2) Kim and Dale[34] estimated the GWI value (gm CO_2 equivalent kg^{-1}) of most fertilisers and chemicals. The GWI value included three GHGs (CO_2, CH_4 and N_2O) and their impact due to agrochemical production, packing, transportation and application. In addition, the GWI factored in GHG emissions of N_2O during the process of de-nitrification after applying nitrogen fertilisers.[34] This method would have been useful if our concern was solely to estimate GHG emissions from agrochemicals and not from all farm operations. As we are estimating GHG emissions due to the production and combustion of fossil fuels separately, there is every chance of duplication, especially for emissions related to the application of agrochemicals. Also, N_2O emission estimates, due to the application of N fertiliser in soils will depend on numerous factors. Research in Australia has shown that for irrigated crops, such as vegetables, the IPCC default value does not apply.[9] Therefore, we did not use this method.

3) National statistical data (such as production area, tonnage of production, and agrochemical application rates) for each vegetable crop were taken from Rab et al.[32] with N, P, K, and S content for each fertiliser estimated using their molecular and atomic weight. Similarly, as suggested in Rab et al.[32] each chemical was multiplied by a conversion factor (0.5 for herbicides and 0.25 for insecticides and fungicides) to obtain the approximate active ingredients. CO_2e emission factors for the production, packaging, storage and transportation of each kg of fertiliser-element (in fertiliser) and active ingredients (in chemicals) were adapted from Lal[31]. Given that Lal[31] provided emission factors in C equivalent, they were converted here into CO_2e (Table 1). This approach overcomes all the problems identified earlier and was thus used in this study.

GHG emissions of N_2O from soils due to the application of N-based fertilisers

Although horticulture (vegetables plus fruits) only occupies 0.1 % of agricultural land in Australia, it accounts for 12 % of N fertiliser use.[9] Lack of oxygen or limited

Table 1. CO_2e ($kgCO_2$ kg^{-1} fertiliser-element (fe) or $kgCO_2$ kg^{-1} active ingredient (ai) chemicals) for production, packaging, storage and transportation of agrichemicals (adapted from Lal [31]).

Fertilisers	*$kgCO_2$ kg^{-1} fe*	*Chemicals*	*$kgCO_2$ kg^{-1} ai chemicals*
N	4.77	Insecticides	18.7
P	0.73	Herbicides	23.1
K	0.55	Fungicides	14.3
S	0.37		
Lime	0.58		

oxygen supply in the soil or high oxygen demand due to more carbon food in the soil causes micro-organisms to utilise nitrate (NO_3^-) and nitrite (NO_2^-) instead of oxygen. The effects of de-nitrification from the applied N-fertiliser, releases N_2O into the atmosphere.[9] N_2O is responsible for 6 % of observed global warming[9] and is currently contributing 6.3 % of Australia's GHG emissions; increasing rapidly from only 4.3 % in 1990.[35] The agricultural sector produces ~80 % of N_2O emissions largely from N fertiliser use and soil disturbance of which 73 % is emitted from agricultural soils.[9]

The IPCC has set default emission factors of 1.25 % NO_2-N emissions per kg of applied N however, there are enormous variations in the IPCC default emission factors. In Australia, the CRC for Greenhouse Accounting has established a set of emission factors suitable for Australian agriculture.[32] Given that the vegetable industry relies on irrigation, we used an emission factor of 2.1 % (2.1 kgN_2O-N per kg-N). After obtaining the total amount of N_2O-N for each vegetable crop, it was converted into N_2O and then into CO_2e. In some cases, farm manures were used in place of N-fertilisers although even organic manures emit some N_2O into the atmosphere. However, there is little available data to quantify these emissions and thus were not considered in this study.

GHG emissions due to the extraction, production and use of electricity for irrigation

The total amount of water and energy (GJ) used for irrigating each type of vegetable was taken from Rab et al.[32] Emission factors for energy use depends on the sources of energy whether renewable or not, and if there is a mix of sources, then what percentage of energy is renewable.[16] In Australia, black and brown coal (40 %) accounted for the greatest share of the fuel source, followed by oil (34 %), natural gas (20 %) and renewables (5 %). However, the fuel mix of each Australian state varies. For example, ~40 % of the energy in Tasmania comes from hydropower, whereas hydropower in Queensland shares <1.5 % of the total energy. The agricultural industry uses either electricity or diesel to pump water for irrigation. The emission factors for energy use for each of the Australian states are given in Table 2.[16]

The DCC regularly updates emission factors for each state, as the energy mix and thus the emission factors may change over time. For the purposes of this study, we use the latest emission factors (the sum of Scope 2 and Scope 3) provided by the DCC.[16] Scope 2 covers emissions solely due to the burning of fuels at power stations, whereas Scope 3 covers indirect emissions attributable to the extraction, production and transport of those fuels. In this study we used the average emission factor of 250 kg $(GJ)^{-1}$ (Table 2).

Table 2. Emission factors for energy consumption in different states.

States	*Emission factors (kCO_2e per GJ)*
NSW and ACT	295
VIC	364
QLD	289
SA	272
WA	271
TAS	37
NT	221
Average	250

Source Australia Dept. of Climate Change (DCC).[16]

GHG emissions due to the extraction, production and use of electricity for cooling, refrigeration, cleaning and packaging vegetables

There are very few studies that describe the methods for the post-harvest electricity (GJ t^{-1}) use for on-farm cooling, refrigeration, cleaning and packaging. A New Zealand study showed that, on average, each hectare of land in New Zealand produces 50 kg of potatoes and 50 kg of onions.[36] The post-harvest electricity use for on-farm operations for potatoes and onions are 0.214 GJ t^{-1} and 0.038 GJ t^{-1}, respectively.[36] In this study we use the same figures for potatoes and onions, the average of both for all other vegetables (0.126 GJ t^{-1}) and the national average emission factor of 250 kCO_2e $(GJ)^{-1}$ for post-harvest electricity use.

GHG emissions due to the production and combustion of fossil fuels used in farms

There are a number of studies documenting GHG emissions due to the production and combustion of fossil fuels. In the Australian context, the Australian Greenhouse Office[37], Beer et al.[38] and the DCC [39] are noteworthy. Consequently, a value of 0.455 kgCO_2e was used in this study for the estimation of GHG emissions in the production of diesel. Similarly, according to the DCC,[39] each kilolitre of diesel produces 38.6 GJ of energy during combustion for transport energy purposes, and the emission factor (relevant oxidation factors incorporated) for each GJ of energy is 69.9 kgCO_2e. Thus each litre of diesel produces 2.698 kgCO_2e during its combustion and the total GHG emissions during the production and combustion of one litre of diesel is 3.15 kgCO_2e. A small amount of GHG emissions occurs during the transportation of fuels, but for the purpose of this study it is not considered, as it is almost negligible.

The total fuel consumed during different farming operations for each vegetable crop was derived from Rab et al.[32] Total fuel consumption and GHG emissions per litre of fuel was used to calculate the total amount of GHG emissions resulting from fuel usage.

Emissions due to the production of farm machinery used by the vegetable industry

Several studies have estimated GHG emissions resulting from the production of a kilogram of farm machinery,[7–8] in particular Maraseni et al.[7] calculated the GHG emissions due to the production of each kg of farm machinery and accessories using Equation 1:

$$\begin{aligned} &\text{GHGs emission (kgCO}_2\text{e/ha)} \\ &\quad = \text{Weight of machinery (kg)} \times \text{GHG emissions/kg} \\ &\quad \times \text{Proportion of lifespan of machinery used} \\ &\quad \text{for given farm activities} \end{aligned} \tag{1}$$

Details about the working life span of farm machinery and accessories were obtained from Harris,[40] and the weight of machines and accessories were sourced from production companies John Deere and AMADAS. The fraction of time a particular machine was used for a particular operation was derived from crop management notes and independently verified by landholders and extension officers.

No published information was available about tractors and other accessories used in the Australian vegetable industry such as the number, types, sizes, and power. Therefore, we decided to use information from Maraseni et al.[7] They concluded that GHG emissions due to the use of farm machinery are directly related to fuel consumption: the greater the use of farm machinery, the higher the fuel consumption. Also, GHG emissions due to farm machinery usage and accessories are 14.4 % of emissions due to fossil fuels in comparable peanut-maize cultivation systems.[7] Since vegetable industry practices are more closely related to peanut-maize cultivations, rather than plantations and pasture, we used this value of 14.4 % in this study. Also, small amounts of GHGs would be emitted while transporting the machinery and accessories but this is negligible and is not considered in this study.

Results

Vegetable farming occupies 112,000 ha of land in Australia. Potatoes are the largest crop by area (30.5 %), followed by lettuce (8.9 %), tomatoes (6.5 %) and broccoli (6.4 %) (Table 3). The following presents details about the quantities of GHG emissions arising from the production of each vegetable crop, each with differing farm inputs. Tables 3 and 4 provide detailed information about the GHG emissions, and also GHG emission rates per hectare and per tonnage for each of the 23 vegetable crops.

GHG emissions due to the production, packaging, storage, and transportation of agrochemicals

In total, the production, packing, storage and transportation of agrochemicals used in the vegetable industry in Australia accounts for ~113,000 tCO_2e emissions each year (Table 3). The four largest crops, which occupy 52.4 % of total vegetable farming areas, account for 55.5 % of GHG emissions. However, the quantities of GHG emissions from these vegetables are not proportional to their cropped areas, except for lettuce which is grown in 8.9 % of cropped areas and emits 8.9 % of the total GHG emissions. Potatoes (35.2 %) and broccoli (10.1 %) account for the highest proportions of GHG emissions relative to their growing areas whilst tomatoes account for the least (1.3 %).

However, GHG emissions varied considerably per hectare and per tonnage for each vegetable crop reported (Table 3). For instance, some of the high volume vegetable crops have less emission rates on a per tonnage emissions basis (Table 3). For example, annual carrot production amounts to >271 tonnes which is the third highest of the 23 vegetables reported in this study, but its GHG emissions rate per hectare is 0.83 $tCO_2e\ ha^{-1}\ yr^{-1}$ and emissions on a per tonnage basis are only 0.02 $tCO_2e\ t^{-1}$, whilst capsicum has the highest emissions rate per hectare (1.86 $tCO_2e\ ha^{-1}\ yr^{-1}$), yet its GHG emission rate on a per tonnage basis of 0.07 $tCO_2e\ t^{-1}$ is much lower than many other vegetables (Table 3).

GHG emissions of N_2O from soils

In total, 188,000 tCO_2e of GHG emissions enter the atmosphere simply through de-nitrification of applied N fertiliser in soils (Table 3). Of the top 4 vegetable producers (potatoes, tomatoes, carrots and lettuce), farmers use less N fertilizer for tomatoes and thus tomatoes (with 6.5 % of the total farming area) account for only 0.3 % of total GHG emissions, whereas potatoes (with 30.5 % of the total farming area) account for 36.6 %. In contrast, broccoli (with 6.4 % of the total farming area) accounts for 10.2 % of emissions. Capsicum and sweet corn, followed by broccoli and green peas-shelled (Table 3) are the highest GHG emitters on a per hectare basis. However, per tonnage, green peas accounts for the highest emissions, followed by broccoli, sweet corn and asparagus (Table 3).

GHG emissions due to electricity use for irrigation

The use of electricity in the vegetable industry accounts for 607,795 tCO_2e of GHG emissions, which represents the single largest source of emissions at 54 % of total emissions. On a per hectare basis, higher emissions come from asparagus, capsicum, pumpkin, sweet corn and zucchini, whilst potatoes, rockmelon, cabbage, lettuce and cauliflower have the lowest emissions (Table 3). However, on a per tonnage basis, green peas and asparagus have the highest emissions whilst mushrooms, carrots and celery are the lowest emitters (Table 3).

Table 3. Greenhouse gas (GHG) emissions from 23 vegetable crops in response to various farm inputs (agrochemicals, N fertiliser and electricity).

			Emissions due to agrochemicals			*Emissions of N_2O from soils due to the use of N-fertilisers*			*Emissions due to the use of electricity for irrigation*		
Crops	*Total area (ha)**	*Production (t)**	(tCO_2e yr^{-1})	(tCO_2e ha^{-1} yr^{-1})	(tCO_2e t^{-1})	(tCO_2e yr^{-1})	(tCO_2e $ha^{-1}yr^{-1}$)	(tCO_2e t^{-1})	(tCO_2e yr^{-1})	(tCO_2e ha^{-1} yr^{-1})	(tCO_2e t^{-1})
Asparagus	1302	5609	667	0.51	0.12	1017	0.78	0.18	10416	8.00	1.86
Beans-french and runner	4978	28844	1784	0.36	0.06	2641	0.53	0.09	29868	6.00	1.04
Beetroot	1279	40765	458	0.36	0.01	679	0.53	0.02	7035	5.50	0.17
Broccoli	7135	46031	11354	1.59	0.25	19208	2.69	0.42	42810	6.00	0.93
Cabbages	2020	81563	2024	1.00	0.02	3324	1.65	0.04	8080	4.00	0.10
Capsicums	2156	56313	4004	1.86	0.07	6779	3.14	0.12	17248	8.00	0.31
Carrots -fresh	5715	271464	4741	0.83	0.02	7861	1.38	0.03	31433	5.50	0.12
Cauliflowers	3580	69793	3294	0.92	0.05	5188	1.45	0.07	14320	4.00	0.21
Celery	991	48542	285	0.29	0.01	351	0.35	0.01	5946	6.00	0.12
Chilies	163	1957	47	0.29	0.02	58	0.35	0.03	978	6.00	0.50
Cucumbers	577	41931	166	0.29	0.00	204	0.35	0.00	3462	6.00	0.08
Green peas - fresh pod	277	533	80	0.29	0.15	98	0.35	0.18	1662	6.00	3.12
Green peas - shelled	3354	15232	4972	1.48	0.33	9029	2.69	0.59	20124	6.00	1.32
Lettuces	10011	271251	10012	1.00	0.04	16475	1.65	0.06	40044	4.00	0.15
Melon - rock & cantaloupe	2628	68105	1364	0.52	0.02	1394	0.53	0.02	10512	4.00	0.15
Melon - water	4421	136861	3510	0.79	0.03	5560	1.26	0.04	35368	8.00	0.26
Mushrooms	181	42739	19	0.10	0.00	16	0.09	0.00	1086	6.00	0.03
Onions	5413	246496	5343	0.99	0.02	9413	1.74	0.04	32478	6.00	0.13
Potatoes	34096	1211988	39712	1.16	0.03	68674	2.01	0.06	136384	4.00	0.11
Pumpkins	5968	102505	4693	0.79	0.05	7505	1.26	0.07	47744	8.00	0.47
Sweet corn	5942	62575	10979	1.85	0.18	18682	3.14	0.30	47536	8.00	0.76
Tomatoes	7293	296035	1465	0.20	0.00	593	0.08	0.00	43758	6.00	0.15
Zucchini/button squash	2438	23704	1905	0.78	0.08	3066	1.26	0.13	19504	8.00	0.82
Total	111918		112877			187815			607795		

Source: Adapted from Rab et al.[32]

GHG emissions involving electricity during on-farm post harvesting activities

On-farm post– harvesting activities include cooling, refrigeration, cleaning and packaging vegetables. In total, on-farm post harvesting activities account for 121,122 tCO_2e emissions (Table 4). Mushrooms have the highest quantities of GHG emissions per hectare, followed by cucumber and potatoes. However, in terms of tonnage, many vegetables have similar GHG outputs with onions having the lowest amount, which is consistent with Barber.[36]

GHG emissions due to fossil fuel usage

Fossil fuels in vegetable farming, account for 73,679 tCO_2e of GHG emissions. More fossil fuels are used per hectare in the production of capsicum, cabbage, asparagus and tomatoes, which are >3 times higher than the lowest emitters such as pumpkins and beetroots (Table 4). In terms of tonnage, green pea (both fresh and shelled) production and asparagus use the highest amounts of fossil fuels, whereas lower amounts of emissions come from mushrooms, onions, potatoes and cucumber (Table 4). There is also significant variation within green pea production with fresh pods requiring more than twice the fossil use per hectare than shelled peas (Table 4).

GHG emissions due to farm machinery usage

GHG emissions due to farm machinery usage are directly related to a heavy reliance upon fossil fuels. Therefore, per hectare, capsicum, cabbage, asparagus and tomatoes have the highest GHG emissions, whilst pumpkins and beetroots have the lowest (Table 4). Similarly, green peas and asparagus are the highest emitters per tonnage, whereas lower amounts of emissions result from mushrooms, onions, potatoes and cucumber (Table 4).

Total GHG emissions

In total, 112,000 ha of vegetable farms account for 1.11 $MtCO_2e$ of GHG emissions (Table 4). Potatoes, which occupy 30.5 % of total vegetable growing area, account for 29.1 % of total emissions; lettuce (occupying 8.9 %) shoulders 7.9 % of total emissions; tomatoes (occupying 6.5 %) shares 5.9 % of total emissions and broccoli (occupying 6.4 %) shares 7.2 % of the total emissions (Table 4).

Capsicum (15.40 $tCO_2e\ ha^{-1}\ yr^{-1}$), followed by sweet corn (14.58 $tCO_2e\ ha^{-1}yr^{-1}$) and mushrooms (14.51 $tCO_2e\ ha^{-1}\ yr^{-1}$), are the highest emitters per hectare, whereas rockmelon (6.36 $tCO_2e\ ha^{-1}\ yr^{-1}$), cauliflower (7.34 $tCO_2e\ ha^{-1}\ yr^{-1}$) and green peas-fresh pod (7.57 $tCO_2e\ ha^{-1}\ yr^{-1}$) were the lowest. Finally, green peas-fresh pod cropping (3.94 $tCO_2e\ t^{-1}$), followed by asparagus (2.54 $tCO_2e\ t^{-1}$) and green peas-shelled farming (2.46 $tCO_2e\ t^{-1}$) were on a per tonnage basis, the highest GHG emitters (Table 4).

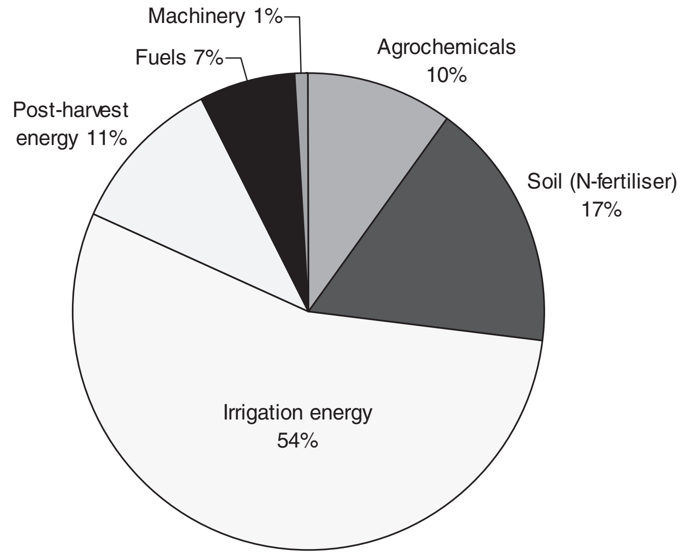

Fig. 1. Greenhouse gas (GHG) emissions from farm inputs/activities in the Australian vegetable industry.

Discussion

The study estimated GHG emissions for 23 vegetables grown commercially in Australia. Analysis revealed that the top four vegetables (potatoes, lettuce, tomatoes and broccoli), are grown in 52.4 % of vegetable farming areas in Australia and account for 51.3 % of GHG emissions. The remaining 19 vegetables are grown in 47.6 % of vegetable farming areas and emit 48.7 % of total GHG emissions attributed to the vegetable industry.

Electricity use for irrigation and post-harvest on-farm activities has the largest proportion of total GHG emissions in the vegetable industry at 65 %, whilst soils N_2O emissions due to N fertiliser use accounts for 17 %, 10 % is due to agrochemical usage, 7 % to farm fuels and 1 % for farm machinery (Fig. 1). These figures highlight three key points: (1) the types of energy sources has a major impact on GHG emissions; (2) water efficient irrigation technology will have an important role in emissions reduction; and (3) N management and reduction of N_2O from soils is critically important.

Energy sources

Given that Tasmania relies heavily on hydropower, it is no surprise to see that it has the lowest emission factors (37 $kCO_2e\ (GJ)^{-1}$) per unit of energy of all states in Australia.[39] With an emissions factor for Australia at 6.76 times that of Tasmania, a vegetable produced in Tasmania would have emitted 4.4 times (0.65 % × 6.76) fewer emissions than that produced on average in mainland Australia. Therefore, if all other factors remain the same, Tasmanian growers are more “greenhouse friendly” than mainland

Table 4. Greenhouse gas (GHG) emissions from 23 vegetable crops in response to various farm inputs (post harvest on-farm activities, fossil fuel usage, total of all farm emissions).

	Emissions due to post harvest on-farm activities			*Emissions due to the use of fossil fuels*			*Emissions due to the use of machinery & accessories*			*Total emissions*		
Crop	(tCO_2e yr^{-1})	(tCO_2 $ha^{-1}yr^{-1}$)	(tCO_2e t^{-1})	(tCO_2e yr^{-1})	(tCO_2e $ha^{-1}yr^{-1}$)	(tCO_2e t^{-1})	(tCO_2e yr^{-1})	(tCO_2e $ha^{-1}yr^{-1}$)	(tCO_2 t^{-1})	(tCO_2e yr^{-1})	(tCO_2e $ha^{-1}yr^{-1}$)	(tCO_2e t^{-1})
Asparagus	177	0.14	0.03	1726	1.33	0.31	249	0.19	0.04	14251	10.95	2.54
Beans - french & runner	909	0.18	0.03	3799	0.76	0.13	547	0.11	0.02	39547	7.94	1.37
Beetroot	1284	1.00	0.03	340	0.27	0.01	49	0.04	0.00	9845	7.70	0.24
Broccoli	1450	0.20	0.03	4369	0.61	0.09	629	0.09	0.01	79820	11.19	1.73
Cabbages	2569	1.27	0.03	2577	1.28	0.03	371	0.18	0.00	18945	9.38	0.23
Capsicums	1774	0.82	0.03	2970	1.38	0.05	428	0.20	0.01	33202	15.40	0.59
Carrots - fresh	8551	1.50	0.03	2422	0.42	0.01	349	0.06	0.00	55357	9.69	0.20
Cauliflowers	2198	0.61	0.03	1115	0.31	0.02	161	0.04	0.00	26276	7.34	0.38
Celery	1529	1.54	0.03	756	0.76	0.02	109	0.11	0.00	8975	9.06	0.18
Chillies	62	0.38	0.03	123	0.75	0.06	18	0.11	0.01	1285	7.88	0.66
Cucumbers	1321	2.29	0.03	441	0.76	0.01	64	0.11	0.00	5657	9.80	0.13
Green peas - fresh pod	17	0.06	0.03	211	0.76	0.40	30	0.11	0.06	2098	7.57	3.94
Green peas - shelled	480	0.14	0.03	2558	0.76	0.17	368	0.11	0.02	37531	11.19	2.46
Lettuces	8544	0.85	0.03	10984	1.10	0.04	1582	0.16	0.01	87642	8.75	0.32
Melon - rock & cantaloupe	2145	0.82	0.03	1140	0.43	0.02	164	0.06	0.00	16720	6.36	0.25
Melon -water	4311	0.98	0.03	3383	0.77	0.02	487	0.11	0.00	52619	11.90	0.38
Mushrooms	1346	7.44	0.03	139	0.77	0.00	20	0.11	0.00	2626	14.51	0.06
Onions	2342	0.43	0.01	2514	0.46	0.01	362	0.07	0.00	52452	9.69	0.21
Potatoes	64841	1.90	0.05	12704	0.37	0.01	1829	0.05	0.00	324145	9.51	0.27
Pumpkins	3229	0.54	0.03	1279	0.21	0.01	184	0.03	0.00	64635	10.83	0.63
Sweet corn	1971	0.33	0.03	6521	1.10	0.10	939	0.16	0.02	86628	14.58	1.38
Tomatoes	9325	1.28	0.03	9491	1.30	0.03	1367	0.19	0.00	65999	9.05	0.22
Zucchini/button squash	747	0.31	0.03	2117	0.87	0.09	305	0.13	0.01	27643	11.34	1.17
Total	121122			73679			10610			1113897		

Note: Total emissions are the sum of Tables 3 and 4.

Australia vegetable growers. However, since Tasmania is far from population centres, food mileage could be an issue.

Water efficient irrigation technology

If the vegetable industry could strive for reduced water demand through more water-efficient irrigation technologies specific to their needs, the impacts on GHG emissions reduction would be significant. A vegetable crop, which requires large volumes of irrigation water, also needs large amounts of energy to pump water to the crop resulting in higher fossil fuel and electricity costs and higher GHG emissions. Precision irrigation technologies, which can help to reduce both irrigation water use and energy consumption, is timely given that Australia is besieged by water shortages, high evaporation rates and an ever-warming climate.

Nitrogen management and N_2O emissions reduction

There are several ways to minimise N_2O emissions from soils due to applied N-fertilisers: (1) maintaining water-filled pore space at <40 %; (2) reducing soil compaction and thus increasing oxygen diffusion in soils; (3) reducing the readily available carbon supply as it enhances microbial proliferation and thus N_2O emissions; and (4) removing residual nitrate from the soil by growing cover crops.[9] In addition, recently, injecting biochar into the soils is becoming a very popular means of reducing N_2O emissions and achieving long-term soil carbon sequestration.[41–42]

GHG emissions: per hectare vs per tonnage

There are a range of results emerging here depending upon whether GHG emissions were being viewed per hectare of growing area or by tonnage of produce. By hectare, there was little variation in the ratio between the highest and the lowest emitting vegetable crops. For instance, capsicum has the highest emissions (15.40 $tCO_2e\ ha^{-1}\ yr^{-1}$) at 2.42 times that of the lowest emitting vegetable, rockmelons (6.36 $tCO_2e\ ha^{-1}\ yr^{-1}$). However, in terms of tonnage, the ratio of emissions between the highest and lowest emitting vegetable crops was quite large. Green peas (fresh pods) had the highest emissions (3.94 $tCO_2e\ t^{-1}$), 65.6 times the emissions of the lowest emitting vegetable crop, mushrooms (0.06 $tCO_2e\ t^{-1}$).

There was also no marked trend in the ranking of vegetable crops GHG emissions on a hectare and tonnage basis. For example, mushrooms have very high GHG emissions (15.40 $tCO_2e\ ha^{-1}\ yr^{-1}$) on a hectare basis, but per tonnage, it has the lowest emissions (0.06 $tCO_2e\ t^{-1}$). This could be due to multiple mushroom crops in a year. Therefore, while estimating GHG emissions for the purposes of the upcoming Australian CPRS and for future carbon labelling of vegetable products, labelling should be based on per tonnage figures.

Advice for the australian vegetable industry in a CPRS

Assuming that: 1) the CPRS becomes a reality; 2) the CPRS covers all vegetable growers without any benchmarking; 3) there is no support for emissions intensive trade exposed industry support; 4) there is no support for fuel credits as proposed in the CPRS[16]; and 5) all on and off farm GHG emissions are covered, then this study is able to provide some guidance for the vegetable industry. Multiplying the carbon price (\$ $t^{-1}CO_2e$) with the figures in the last column of Table 4 for each vegetable crop will identify how much extra burden the vegetable industry needs to bear if it is covered under the CPRS. However, this is a national level study and this should be used only as a guide, as variations will exist between states and regions. Also, the quantity of emissions, and therefore the emissions burden, will vary by edaphic, climatic and topographic factors, and farm inputs and management practices. Therefore, potatoes produced even in one part of Queensland could have a significantly different GHG emission factor than those produced in another part of Queensland.

Under the current CPRS provisions, however, it is unlikely that the vegetable industry will be covered. Even if agriculture is covered, vegetable farms may not come under the CPRS, as CPRS only covers entities with emissions >25,000 tCO_2e/yr. Our analysis has revealed that on average, a hectare of vegetable farm accounts for ~9.2 $tCO_2e\ ha^{-1}\ yr^{-1}$. To be covered under the CPRS, a vegetable farm would need to occupy at least 2,700 ha of land, which is highly improbable.

Conclusions

This study estimates GHG emissions for 23 commercially grown vegetable crops in Australia. The vegetable industry in Australia occupies 121,122 ha of land with a gross value of \$3.22 billion in 2007–2008 to the Australian economy[2] accounting for 1.114 M tCO_2e GHG emissions at an average of 9.2 $tCO_2e\ ha^{-1}$. The top four vegetables by area grown are potatoes, lettuce, tomatoes and broccoli, which account for 29.1 %, 7.9 %, 5.9 % and 7.2 % of total GHG emissions, respectively. Whilst higher emissions per hectare result from capsicum, sweet corn and mushroom farming per tonnage, green peas and asparagus are the prime GHG contributors. By hectare, GHG emissions from the lowest–emitting vegetable (rockmelon) are 2.42 times lower than from the highest–emitting vegetable (capsicum). However, by tonnage, the ratio between the highest– and lowest–emitting vegetable is very high (65.6). Also, the ranking of vegetable crop emissions vary significantly whether the focus is on a hectare or tonnage basis. For example, mushroom crops have the second highest emissions per hectare, but the lowest emissions per tonnage. This is due to the fact that mushrooms are grown several times per year in a given area and thus production per hectare is always very high. Therefore, carbon labelling of vegetable products should provide consumer information based on a per tonnage calculation rather than per hectare of cropping.

The two largest sources of GHG emissions from the vegetable industry are electricity used for irrigation and post-harvest on-farm activities (65 % of total emissions), and soils N_2O emissions due to use of N fertilisers (17 % of total emissions). As Tasmania uses large amounts of hydroelectricity, its emission factor per unit of energy is 6.76 times lower than the national average. Therefore, Tasmanian farmers contribute 4.4 times less GHG emissions, on average, for the same produce compared to mainland farmers. The replacement of coal-fired power with renewable energy sources (such as solar) in these other Australian states will provide similar opportunities. In addition, maintaining soil pore water-filled spaces at <40 %, increasing soil oxygen diffusion, reducing readily available soil carbon supply and removing residual nitrate from soils by growing cover crops could reduce soil N_2O emissions.[9]

This study provides some valuable guidelines for the vegetable industry and key stakeholders. Firstly, it presents consumers with choices and additional information about vegetables on the basis of their contribution to GHG emissions. As consumers are becoming more carbon conscious, their decisions to buy certain vegetables may be determined by the labelled carbon levels. Secondly, it provides a product branding/marketing opportunity for producers. More carbon conscious producers could strategically help to improve their own profits. Thirdly, it provides insights for farmers and policy makers about the source and magnitude of GHG emissions in the sector and can help to focus industry attention to reduce future emissions. Fourthly, it presents some basic data for developing a carbon calculator for the Australian vegetable industry. Finally, it provides some insights to policy makers about where the vegetables industry is positioned relative to national GHG emissions and whether it should be considered in the CPRS in the future.

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