

# Global warming potential of wheat production in Western Australia: a life cycle assessment

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## Keywords

cereal production; global warming; life cycle assessment; nitrous oxide.

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## Abstract

This study presents a greenhouse gas (GHG) life cycle assessment of 1 tonne of wheat transported to port in south-western Australia, including emissions from prefarm, onfarm and postfarm stages. The prefarm stage included GHG emissions from agricultural machinery, fertiliser and pesticide production. The onfarm stage included GHG emissions from diesel use, liming and nitrous oxide (N<sub>2</sub>O) emissions from N fertiliser applications. The postfarm stage included grain storage and transportation to the port. GHG emissions decreased from 487 to 304 kg carbon dioxide (CO<sub>2</sub>) equivalents when we used regional-specific data for N<sub>2</sub>O emissions instead of the IPCC default value for the application of synthetic N fertilisers to land (1.0%). Fertiliser production in the prefarm stage contributed significantly (35%) to GHG, followed by onfarm CO<sub>2</sub> emissions (27%) and emissions from transportation of inputs and wheat (12%). N<sub>2</sub>O emissions from paddock represented 9% of the total GHGs emitted. We recommend utilising regionally specific data for soil N<sub>2</sub>O emissions, rather than international default values, when assessing GHG for agricultural production systems.

## Introduction

Nitrous oxide (N<sub>2</sub>O) concentrations in the earth's atmosphere have increased from 275 to 319 ng/g since the industrial revolution (Dentener *et al.* 2001; Houghton *et al.* 2001; World Meteorological Organization 2006). This is of concern as N<sub>2</sub>O contributes to global warming and destruction of the ozone layer. Although N<sub>2</sub>O is only present as a trace gas in the earth's atmosphere, it has 310 times the global warming potential of carbon dioxide (CO<sub>2</sub>) and a lifespan of 120 years (Crutzen 1981). N<sub>2</sub>O emissions from agricultural soils are considered to account for 70–81% of the increase in the earth's atmosphere, which has been linked to a global increase in nitrogen (N) fertiliser use (Bouwman 1990). Consequently, there have been many studies investigating the nature and extent of N<sub>2</sub>O emissions from agricultural soils (Stehfest & Bouwman 2006), plus approaches to mitigating these losses (Mosier *et al.* 1998).

In agricultural production systems, other greenhouse gases (GHGs) (CO<sub>2</sub>, CH<sub>4</sub>) in addition to N<sub>2</sub>O can be emitted. A holistic approach is therefore needed if the

overall impact of agricultural production systems on global greenhouse emissions is to be addressed. For example, a 'life cycle assessment' (LCA) can be undertaken to account for all GHGs emitted for crop production so that mitigation strategies focus on the primary sources of GHG emissions. An LCA compiles the inputs and outputs from a production system, and in turn evaluates their potential environmental impacts (e.g. GHG emissions) (Ekvall & Finnveden 2001; Greadel & Allenby 2003a, b). This has the advantage of identifying the environmental impacts of all stages in the production cycle rather than focusing on a single source of GHG emission (e.g. N<sub>2</sub>O emission from the application of N fertiliser to land). Furthermore, LCA enables evaluation of environmental impacts for comparative or improvement purposes (e.g. Braschkat *et al.* 2003).

Semi-arid and arid lands constitute one-third of the global land area and are widely used for agricultural production (Harrison & Pearce 2000). Understanding GHG emissions from agricultural soils in these regions is necessary if we are to improve our knowledge of terrestrial global emissions. LCA of GHG emissions from arable

systems in semi-arid regions does not appear to have been reported. Instead, assessments of cropping systems have mainly been confined to European bread production (Braschkat *et al.* 2003); the production of corn and corn–soybean rotation (Heller & Keoleian 2000; Robertson *et al.* 2000), plus the manufacture of biodiesel from *Brassica carinata* and rape methyl (Kaltschmitt *et al.* 1997; Gasol *et al.* 2007). While extrapolating findings from these studies to other parts of the world is inappropriate because of differences in crop type, climate and production systems (factors known to influence agricultural GHG emissions), these studies have demonstrated the significant impact of N fertiliser utilisation on GHG emissions from crop production. Yet, most of the aforementioned studies have assumed the international default value, including IPCC and US EPA GHG inventory values for the proportion of N fertiliser emitted as N<sub>2</sub>O, rather than utilising a regional-specific value (Kaltschmitt *et al.* 1997; Heller & Keoleian 2000; Robertson *et al.* 2000; Gasol *et al.* 2007).

The south-western Australian grain belt consists of approximately 18 million ha of semi-arid land and is responsible for 40% of Australia's annual grain production. The Australian Grains Industry is seeking to maintain a clean, green industry to guarantee its long-term productivity, and to ensure access to premium markets by giving attention to its Environmental Supply Chain Management, of which LCA of GHG emissions is a supporting instrument. The aim of the following paper is to present the life cycle global warming potential of wheat production in south-western Australia by (a) identifying the main processes contributing to GHG emissions from pre-farming, onfarm and postfarming stages and (b) comparing GHG emissions calculated using locally derived N<sub>2</sub>O emissions (Barton *et al.* 2008) with those calculated using the international default value [1.0% of N fertiliser applied (IPCC 2006)].

## Materials and methods

To determine the global warming potential of wheat production in south-western Australia, we compiled and evaluated the inputs (e.g. fertiliser, pesticides) and outputs (e.g. CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O) required to produce 1 tonne of wheat from a site (Cunderdin, 31°36'S, 117°13'E) located in the central wheat belt of Western Australia.

Cunderdin has a semi-arid climate, with an annual rainfall of 368 mm, which mainly falls during the winter months, a mean daily maximum temperature of 25.1 °C and a mean daily minimum temperature of 11.4 °C (Commonwealth of Australia 2007). The soil is a free-draining sandy soil overlying a poorly draining clay, with low chemical fertility throughout the soil profile. For further details about the study site and the measurement of in situ N<sub>2</sub>O emissions, the reader is referred to Barton *et al.* (2008).

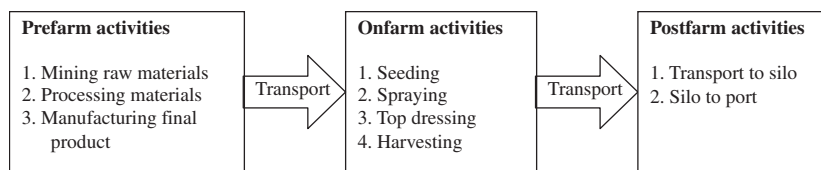
The LCA approach used in this paper assessed GHG emission for pre-farming (e.g. manufacture of farming equipment), onfarm (e.g. planting the crop) and post-farming stages (e.g. delivery of grain to port) separately for wheat production at the study site. Using this approach enabled the GHG emissions from fertiliser use (manufacture and application), transportation, storage and combustion of diesel to be calculated. The LCA follows the ISO14040-43 guidelines ISO (1997) and is divided into four steps: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment and (4) interpretation (as presented in the 'Results' of this paper).

## Goal and scope

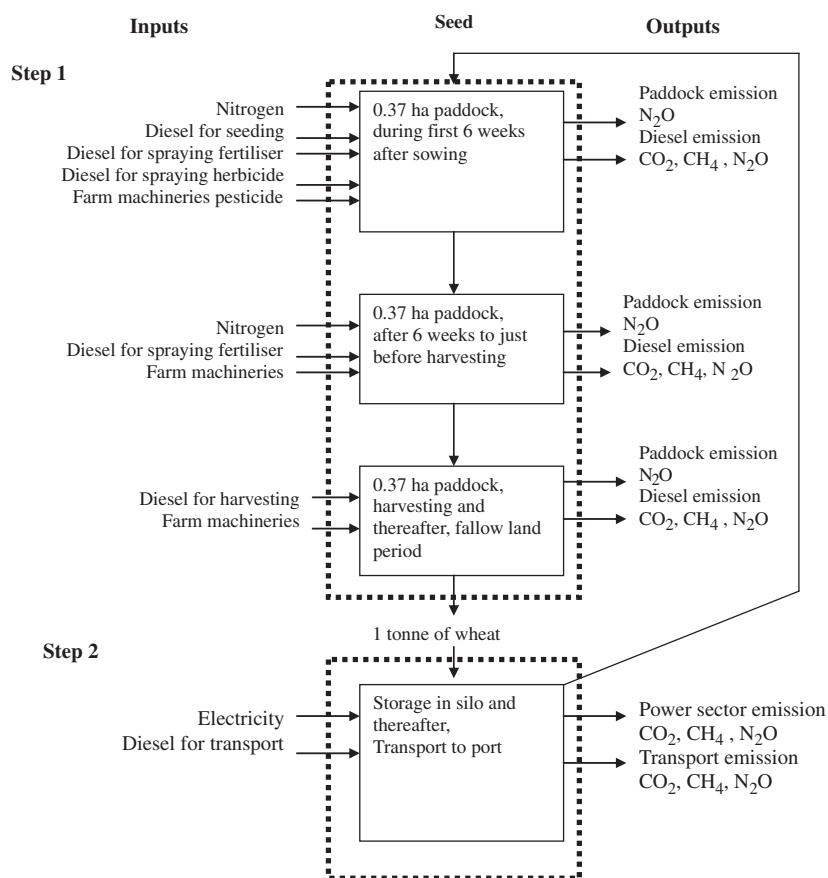
The goal was to estimate the total GHG emitted during the production of rain-fed wheat from a farm in south-western Australia by the LCA process. This was achieved by establishing the functional unit, selecting the relevant system boundaries and determining data requirements. The functional unit was 1 tonne of wheat transported to port for interstate or international trading. Because the proportion of wheat transported to different states and countries varies from year to year, the boundary to the LCA was limited to the port only.

The LCA was divided into three main stages: prefarm, onfarm and postfarm (Fig. 1). Prefarm data included information on the production of inputs, such as N fertiliser, pesticides and diesel, and also combustion of the latter in transporting the inputs to the farm. The postfarm stage included transportation of 1 tonne of wheat from the farm to the local bin, wheat storage and the transportation of wheat to port.

Onfarm activities were based on a 12-month field study (from sowing) conducted at the Cunderdin Agricultural



**Fig. 1.** Life cycle inventory of wheat production from manufacture of inputs to commodities transported to port.



**Fig. 2.** Life cycle inventory of 1 tonne of wheat harvested for onfarm and postfarm stages.

College (May 2005 to May 2006). The on-farm stage was further divided into three periods: first 6 weeks after sowing (25 kg N/ha applied as urea at seeding); from 6 weeks to harvesting (75 kg N/ha applied as urea at week 6) and harvesting to 12 months, which was when the land lay fallowed. An equivalent of 2.7 tonne/ha of wheat was harvested from the site, and therefore we assessed GHG emissions from the production and transport of 1 tonne of wheat from 0.37 ha of N fertilised land. A land preparation stage was not included in the analysis, as minimum tillage is common practice in the area.

Total soil N<sub>2</sub>O emissions measured during the onfarm stage were 0.11 kg N/ha/year (Barton *et al.* 2008). In addition to N<sub>2</sub>O, we also calculated CO<sub>2</sub> emission from the hydrolysis of urea (i.e. 20% of the urea; IPCC 2006). CO<sub>2</sub> uptake from crop growth was not considered as much of the plant material was retained on site following harvest, and we assumed that the sequestered CO<sub>2</sub> would be re-released with time. Soil C sequestration was also not included in our analysis as it is not considered to be significant during a 12-month period. Soil CH<sub>4</sub> emission and/or uptake was not included because of the absence of data rain-fed crops for semi-arid regions; furthermore, CH<sub>4</sub> emissions/uptakes are expected to be low from

fertilised agricultural soils (Suwanwaree & Robertson 2005).

### Inventory analysis

A life cycle inventory (LCI) considers the amount of each input and output for processes that occur during the life cycle of a product. Undertaking an LCI is a necessary initial step in order to carry out an LCA analysis.

In the present study, onfarm activities (Step 1 in Fig. 2) included information on inputs, such as N fertiliser production and application, diesel combustion by machinery for each of the onfarm periods, and transportation of these inputs during these stages. The inputs (Fig. 2) are the chemicals, energy and machinery required to produce 1 tonne of wheat. The gases under the outputs column of the inventory represent GHG emissions (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O) from the onfarm stage. Later, these gas emissions were converted to kg CO<sub>2</sub>-equivalents (Table 1). Input information (Fig. 2) was collected by interviewing local farmers involved in growing wheat at Cunderdin. Step two of the LCI was the postfarm activities of two elements: local wheat storage (i.e. in a bin) and transportation of the wheat to port (Fig. 2).

## Impact assessment

The environmental impact assessment of wheat production for prefarm, onfarm and postfarm activities included two stages. The first calculated the total gases produced in each process and the second converted these gases to CO<sub>2</sub> equivalence.

*Stage 1:* The input and output data in LCI were inserted into the Simapro 7 (2006) software to calculate GHG from wheat production. The input/output data of LCI were linked to relevant libraries in Simapro 7. The LCA library is a database that consists of energy consumption, emission and materials data for the production of 1 unit of a product. The units of input and output data of LCI depend on the units of the relevant materials (i.e. kg, L, MJ, \$ etc.) in Simapro or the libraries.

**Libraries for chemicals:** The Australian LCA database (RMIT 2005) was used to calculate GHG emissions from the production of chemical inputs such as pesticides, limestone and urea. The emission factor for single super phosphate was obtained from the fertiliser manufacturer (CSBP Ltd., Perth; C. Schuster, pers. comm.) because the data were unavailable from RMIT (2005). The supply chain of urea and pesticide, including production and transportation to the point of use, was incorporated in order to assess the GHG emissions during the prefarm stage. For the Cunderdin site, a 30 tonne articulated truck, which is widely used in rural Australia, travelled 180 km to carry diesel and pesticide to the farm, and also travelled 153 km to carry fertiliser to the paddock. The unit for

transport library is tonne-kilometre (tkm). In this case, 0.4 tkm is required to carry 1 kg of pesticide or fertiliser for 400 km (i.e. 0.001 tonne × 4 km). Transportation was equivalent to 0.076, 86 × 10<sup>-4</sup> and 13 × 10<sup>-4</sup> kg/tkm for CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O, respectively (RMIT 2005).

**Farm machinery library:** A USA input-output database was used to assess the GHG emitted from manufacturing farm machinery used to produce 1 tonne of wheat (Suh 2004). This database contains environmental emission data for the production of US\$ 1 equivalent farm machinery. Table 2 shows the lifetime operational time of farm machinery and their costs, which are required to determine the cost per hectare. The current price of farm machinery was deflated to the 1998 price (in AUD) at 3% per year. Following this, the 1998 price of machinery in AUD/hectare has been converted into 1998 US\$ by multiplying by 0.6.

**Farm machinery operation library:** Farm machinery (Table 2), which consumes <500 MJ/ha, is regarded as light duty machinery (Nemecek *et al.* 2004). Therefore, the library for light duty agricultural machinery (RMIT 2005) was used to calculate the potential GHG emitted from farm machinery operation. The emission factors for CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O are 0.0694, 2.8 × 10<sup>-6</sup> and 2.6 × 10<sup>-6</sup> kg/MJ, respectively.

**Electricity library:** A wheat bin consumes approximately 0.14 kWh of electricity for every 1 tonne of wheat (Altham *et al.* 2004). The library for Western Australian electricity generation mix was used to calculate GHG emission from electricity generation (RMIT 2005).

**Libraries for storage and transportation to port:** Storage time varies from a day to a year; however, an average emission factor for wheat storage was taken from Altham *et al.* (2004), which is 4.57 kg CO<sub>2</sub>-equivalent per tonne of grain storage. Emission factors for transportation of wheat from farm to local bin, and bin to port were considered to be the same as those presented in the previous section. The distance from the paddock to the bin in the nearby town of Cunderdin was 3 km, and the distance from the bin to port (Kwinana, Western Australia) was 180 km.

**Table 1** Conversion factor for selected greenhouse gases<sup>a</sup>

GHGs	Conversion factor	Unit
CO <sub>2</sub>	1	kg CO <sub>2</sub> -equivalent/kg of CO <sub>2</sub>
CH <sub>4</sub>	21	kg CO <sub>2</sub> -equivalent/kg of CH <sub>4</sub>
N <sub>2</sub> O	310	kg CO <sub>2</sub> -equivalent/kg of N <sub>2</sub> O

<sup>a</sup>RMIT (2005)

GHGs, greenhouse gases; CO<sub>2</sub>, carbon dioxide; CH<sub>4</sub>, methane; N<sub>2</sub>O, nitrous oxide.

**Table 2** Cost and operation of farm machinery for wheat production

Name of machine	Operational time <sup>a</sup> (h/ha)	Life time (h) <sup>a</sup>	Cost		
			(AUD, 2006 price)	(AUD/ha, 2006 price)	(AUD/ha, 1998 price) <sup>b</sup>
Seeder	0.12	8640	90 000	1.28	1.04
Sprayer	0.02	8640	70 000	0.16	0.13
Tractor (125 HP) for seeding	0.12	8640	125 000	1.78	1.45
Tractor (125 HP) for spraying	0.02	8640	125 000	0.29	0.23
Harvester	0.08	7200	442 914	5.09	4.14

<sup>a</sup>CECP (2005).

<sup>b</sup>Have been deflated to 1998 price at 3% per year.

**Table 3** GHG emissions in three stages of the life cycle of 1 tonne of wheat transported to port

Stages	Greenhouse gases			kg CO <sub>2</sub> equivalent			Total kg CO <sub>2</sub> equivalent
	CO <sub>2</sub> (kg)	N <sub>2</sub> O (kg)	CH <sub>4</sub> (kg)	CO <sub>2</sub> kg CO <sub>2</sub> equivalent	N <sub>2</sub> O	CH <sub>4</sub>	
<i>Prefarm</i>							
Farm machinery production	0.93	5E-05	1E-04	0.93	0.01	0.00	0.94
Production and supply of urea	79.25	0.06	0.25	79.25	19.51	5.11	103.87
Production and supply of superphosphate <sup>1</sup>				2.93			2.93
Production and supply of pesticide	17.15	0.04	0.04	17.14	10.14	0.69	27.97
Subtotal				100.25	29.66	5.80	135.71
<i>Onfarm</i>							
N <sub>2</sub> O emissions from paddock (Barton <i>et al.</i> 2008)		0.09			26.98		26.98
CO <sub>2</sub> emissions from paddock (IPCC 2006)	81			81.00			81
Diesel supply and utilisation for spraying fertiliser	4.65	1E-04	6E-04	4.64	0.04	0.01	4.69
Diesel supply and utilisation for spraying herbicide	2.32	5E-05	3E-04	2.31	0.01	0.01	2.33
Diesel supply and utilisation for spraying seeds	9.24	2E-04	0.001	9.23	0.07	0.03	9.33
Diesel supply and utilisation for harvesting	9.24	2E-04	0.001	9.23	0.07	0.03	9.33
Subtotal				106.41	27.17	0.08	133.66
<i>Postfarm</i>							
Wheat storage	5.63	5E-6	3E-5	5.64	1E-3	1E-3	5.642
Transport to port	16.08	0.028	0.181	16.08	8.77	3.80	28.65
Subtotal				21.72	8.77	3.80	34.29
Grand total				228.38	65.60	9.68	303.66

<sup>1</sup>Only kg CO<sub>2</sub> equivalent information has been obtained from Schuster (pers. comm.)

GHG, greenhouse gas; CO<sub>2</sub>, carbon dioxide; N<sub>2</sub>O, nitrous oxide.

*Stage 2:* Simapro software calculated the GHG emissions once the inputs and outputs were linked to the relevant libraries. The program sorted GHG from the selected libraries, and then converted each selected GHG to CO<sub>2</sub> equivalents (Table 1).

## Results

### LCA using measured in situ N<sub>2</sub>O emissions

The equivalent of 304 kg of CO<sub>2</sub> was produced during the production and delivery of 1 tonne of wheat to port (Table 3). CO<sub>2</sub> contributed 228 kg (75% of total), CH<sub>4</sub> contributed 10 kg CO<sub>2</sub>-equivalents (3%) and N<sub>2</sub>O contributed 66 kg CO<sub>2</sub>-equivalents (22%) (Fig. 3a). Prefarm, onfarm and postfarm stages accounted for 136 kg CO<sub>2</sub>-equivalents (45% of total), 134 kg CO<sub>2</sub>-equivalents (44%) and 34 kg CO<sub>2</sub>-equivalents (11%), respectively. For the pre-farm stage, CO<sub>2</sub> was the main GHG emitted (i.e. 100 kg CO<sub>2</sub>-equivalents), and resulted from the supply of diesel, fertilisers, pesticides and machinery (Table 3). CO<sub>2</sub> resulting from the combustion of diesel by farm machinery and the application of urea was the greatest source of GHG emissions for the onfarm stage, followed by N<sub>2</sub>O from the application of N fertiliser to land (Fig. 3a). CO<sub>2</sub> emitted from transporting grain to port was the greatest source of GHG for the postfarm stage.

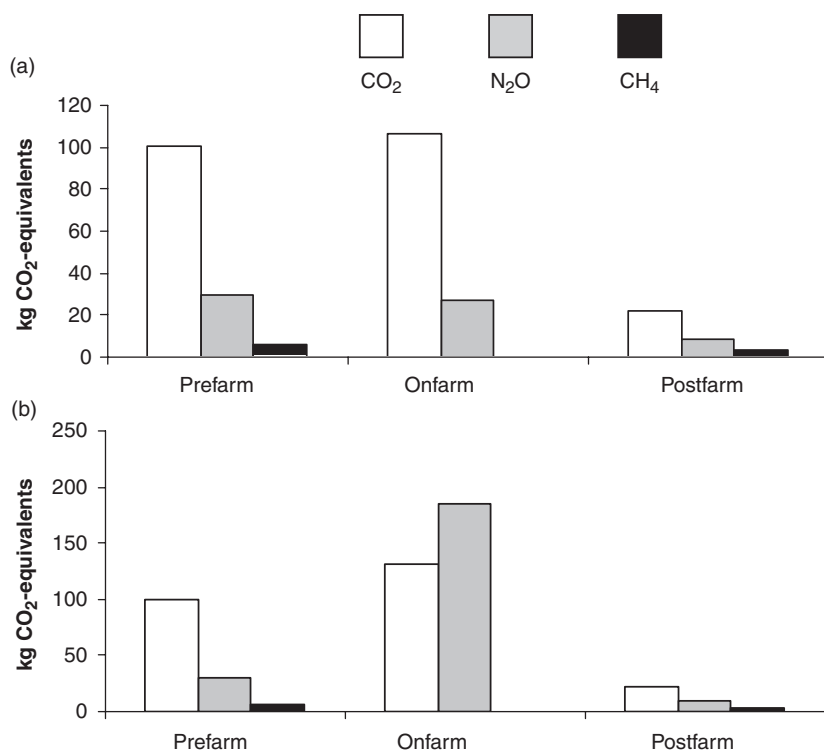
Overall, the production and supply of fertiliser accounted for a large proportion (35%) of GHG emission

produced from wheat production, and occurred in the prefarm stage (Fig. 4a). Other significant sources of GHG emissions included CO<sub>2</sub> emission from the hydrolysis of applied urea (27%), transportation of inputs and wheat (12%), herbicide production (9%), N<sub>2</sub>O emissions from N fertiliser application (9%) and operation of farm machinery (8%). Because CO<sub>2</sub> emissions from the production of farm machinery were not large (0.3%), it was not used further in analyses.

CO<sub>2</sub> and N<sub>2</sub>O were the main gases produced during three periods of onfarm stage (Fig. 5). About 42, 68 and 24 kg CO<sub>2</sub>-equivalent GHG were emitted during the first (first 6 weeks after sowing), second (after 6 weeks to harvesting) and third (harvest and thereafter fallow land period) periods, respectively. The emission of CO<sub>2</sub> was predominant during the first 6 weeks after sowing, because urea breakdown and diesel combustion by farm machinery for seeding and spraying operations were the principal sources during this period. N<sub>2</sub>O, however, was the main GHG emitted directly after summer rain storms, which occurred in the fallow period postharvest and was likely to be due to wetting of the dry soil and increased nitrification activity.

### LCA using international default value for N<sub>2</sub>O emissions

The amount of life cycle GHG emissions from the transportation of 1 tonne of wheat to port increased to



**Fig. 3.** Greenhouse gas emissions (CO<sub>2</sub> equivalents) during prefarm, onfarm and postfarm activities, (a) using Barton *et al.* (2008) emission factor for N<sub>2</sub>O and (b) using IPCC (2006) emission factor for N<sub>2</sub>O (1.0%).

487 kg CO<sub>2</sub>-equivalents when the proportion of N<sub>2</sub>O emitted from the application of N fertiliser to land was assumed to be 1.0% (Fig. 3b). Prefarm, onfarm and postfarm stages accounted for 136 kg CO<sub>2</sub>-equivalents (28% of total), 317 kg CO<sub>2</sub>-equivalents (65% of total) and 34 kg CO<sub>2</sub>-equivalents (7%), respectively (Fig. 4b). N<sub>2</sub>O from N fertiliser application during the onfarm stage was the greatest single source of GHGs (36% of total, 175 kg CO<sub>2</sub>-equivalents) (Fig. 4b). The second largest source of GHGs was the production of fertiliser in the prefarm stage (24%, 117 kg CO<sub>2</sub>-equivalents).

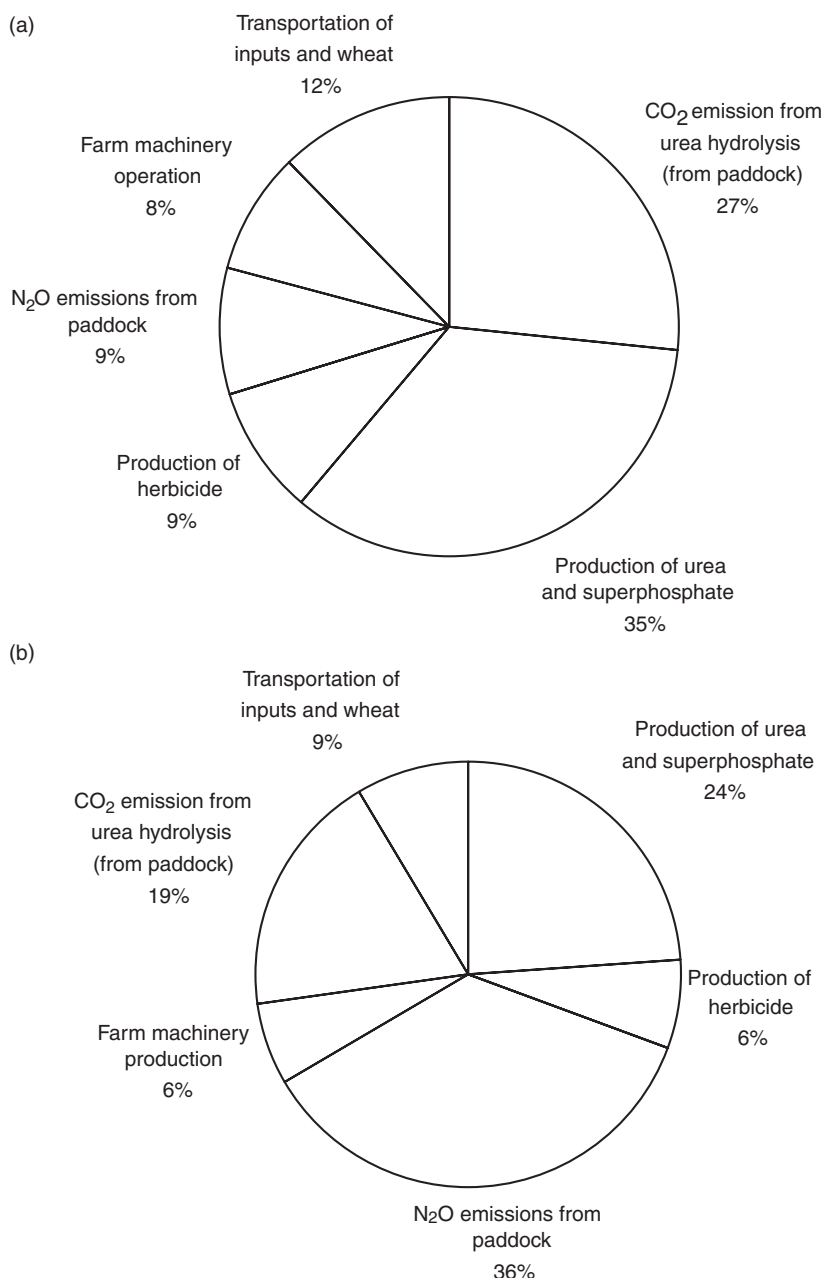
## Discussion

### GHG emissions from the production and delivery of wheat to port

Utilising regionally specific data for soil N<sub>2</sub>O emissions, rather than international default values, can markedly affect the GHG emissions calculated for an agricultural production system. In the present study, incorporating site-specific data decreased the total GHG emissions calculated for the production of wheat by 38% and decreased calculated soil N<sub>2</sub>O emissions by almost 85%. This was because the measured N<sub>2</sub>O emissions represented a much lower proportion of the applied N (0.02%), which was approximately 50 times less than the default value suggested by the IPCC for calculating

N<sub>2</sub>O emissions from cropped soils (1.0%) (IPCC 2006). Barker-Reid *et al.* (2005) similarly reported low emissions from a rain-fed wheat crop in a temperate region of south-eastern Australia where annual emissions ranged from 0.20 to 0.27 kg N<sub>2</sub>O-N/ha (0.06–0.11% of N fertiliser applied) depending upon tillage and fertiliser management. Given that globally, and across a variety of climatic regions, a range of annual N<sub>2</sub>O losses (0.3–16.8 kg N<sub>2</sub>O-N/ha/year) have been reported for cropped mineral soils (Stehfest & Bouwman 2006), we recommend including regional-specific data to accurately assess GHG emissions from wheat production.

The main source of GHG emissions from the production and transport of wheat in a semi-arid environment, such as the central grain-belt of Western Australia, is likely to differ from other regions. In the present study, the production of urea was the single largest source of GHG emissions (35%), followed by onfarm CO<sub>2</sub> emissions (27%) and emissions from the transportation of grain and farm inputs (12%). Similarly, Gasol *et al.* (2007) also concluded that emissions from the production of fertiliser accounted for a significant portion (i.e. 40–50%) of the total GHG during the production of *Brassica carinata* in a hectare of land in 1 year. By contrast, others who have concluded onfarm emissions, rather than prefarm or postfarm emissions, contribute significantly (33–54%) to total GHG emissions, as a result of the application of synthetic N fertilisers to the crop (Sheehan *et al.* 1998;

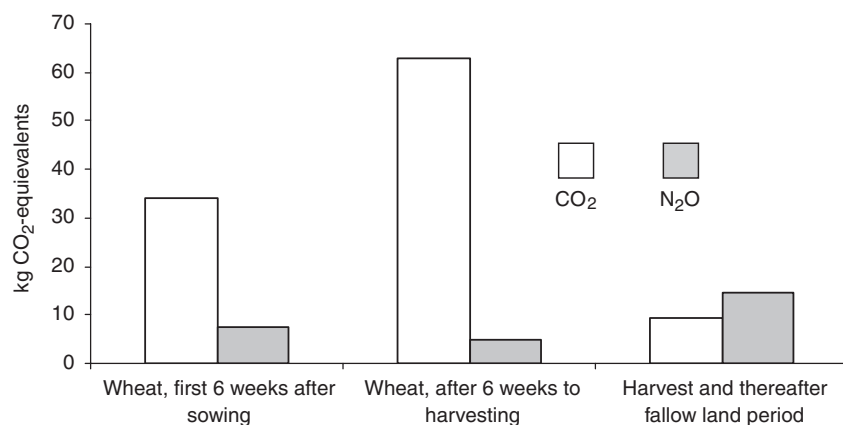


**Fig. 4.** Percentage contributions of greenhouse gas emissions (CO<sub>2</sub> equivalents) in terms of inputs and outputs for wheat production (a) using Barton *et al.* (2008) emission factor for N<sub>2</sub>O and (b) using IPCC (2006) emission factor for N<sub>2</sub>O (1.0%).

Braschkat *et al.* 2003). The large contribution of onfarm activities to the total GHG emissions in the previous studies can be attributed to the larger amount of N<sub>2</sub>O considered to be emitted from crop cultivation. For example, Sheehan *et al.* (1998) estimated that 3.60–5.20 kg N<sub>2</sub>O-N/ha was emitted from the cultivation of corn for biodiesel production, whereas in the present study 0.11 kg N<sub>2</sub>O-N/ha was produced. Robertson *et al.* (2000) also found that the emission of N<sub>2</sub>O during the on-farm stage accounted for 77% of the total GHG emission. If the regional-specific data had not been included in the

present study, and the international default value used instead, we would have incorrectly concluded that N<sub>2</sub>O emissions from the application of N fertiliser to land was the main source (40%) of GHG emissions from the production and supply of wheat.

N<sub>2</sub>O emissions from land contribute significantly to 'onfarm' GHG emissions from wheat production in semi-arid regions, even when measured losses are significantly less than that predicted using the IPCC default value. For example in the present study, and despite the low amount of N<sub>2</sub>O produced (27 kg CO<sub>2</sub>-equivalent per



**Fig. 5.** Onfarm greenhouse gas emissions for 1 tonne of wheat (kg CO<sub>2</sub>-equivalent) production.

tonne of wheat, Table 3), these emissions still accounted for 20% of the total GHG (in CO<sub>2</sub> equivalents) emitted from the onfarm stage due to the high global warming potential of N<sub>2</sub>O (310 kg CO<sub>2</sub>-equivalents per kg of N<sub>2</sub>O). Similarly, N<sub>2</sub>O emission has been found to be predominant in the onfarm stage for food production from agriculture in the United States (Andersson & Ohlsson 1999; Heller & Keoleian 2000). Indeed in the present study, over half of all the N<sub>2</sub>O produced in the production and supply of wheat occurred from the onfarm stage, with the remaining emitted in the postfarm stage via transportation of the grain from the local silo to the port using an articulated truck ( $13 \times 10^{-5}$  kg N<sub>2</sub>O/tkm).

Limestone is often applied to arable soils to ameliorate soil acidity, but can potentially increase the amount of GHG emitted from wheat production. In the present study, 'liming' was not considered in the LCA as lime was not applied during the study period; however, approximately 370 kg of lime (per 1 tonne of wheat) was applied to the study site the previous year. We estimate that applying 370 kg of lime would emit 162 kg CO<sub>2</sub> from the soil, based on the IPCC emission factor for the application of lime to land (IPCC 2006), plus a further 4 kg CO<sub>2</sub> would be emitted from the lime manufacturing stage. Including liming in the present LCA would increase the total emission of GHG from 304 kg CO<sub>2</sub>-equivalents to 466 kg CO<sub>2</sub>-equivalents per tonne of wheat. However, care should be taken when calculating CO<sub>2</sub> emissions from liming, as recent research would suggest that the IPCC default value may overestimate CO<sub>2</sub> emissions from the application of lime to land (West & McBride 2005; Hamilton *et al.* 2007). The impact of liming on GHG emissions clearly needs further investigation if we are to confidently include this practice in LCAs for grain and food production.

The functional unit of an LCA analysis has a large bearing on the conclusions drawn. For example, we expect that the implications of the present study may have differed if the analysis included the production of

bread from harvested wheat. Other studies, including all stages of crop life cycle or 'paddock to plate', have found that either the manufacturing process of the finished product or the use of finished product has contributed more to GHG emissions than prefarm and onfarm stages (Heller & Keoleian 2000). For example, in the life cycle of ethanol production from cassava, almost 96% of CH<sub>4</sub> and 99% of N<sub>2</sub>O emissions are mainly related to the burning of the stem of cassava and 42 and 57% of CO<sub>2</sub> emissions are from the production of the unit of denatured ethanol and the burning of the unit of ethanol gasoline, respectively (Leng *et al.* 2008).

### Mitigating GHG emissions from the production and delivery of wheat to port

The LCA analysis presented in this paper suggests that decreasing GHG emissions from the production of urea fertiliser and the use of transportation fuel could have a large impact on GHG emissions from the production and delivery of wheat. A reduction in GHG emissions from synthetic N fertiliser production might be achieved by introducing cleaner production strategies in the urea production process and by considering plant capacity utilisation, type of feedstock, technology used and age of the plant (Schumacher & Sathaye 1999). Alternatively, the production or demand for synthetic N fertilisers, and therefore GHG emission, might be decreased by replacing chemical fertilisers with organic N fertilisers. For example, it had been suggested that ~80% CO<sub>2</sub>-equivalent emissions could be mitigated from the onfarm stage by substituting chemical fertiliser for organic fertiliser (Braschkat *et al.* 2003). However, the substituting synthetic N fertiliser with organic fertiliser requires further research for Australian situations as extrapolation of findings from other parts of the world may not be appropriate due to differences in soil types, climate and production systems.

In terms of reducing GHG emissions from transportation and farm machinery, biodiesel and liquid petroleum gas (LPG) might be an alternative fuel to diesel for farm machinery and transportation. For example, from a life cycle greenhouse emission perspective, biodiesel produced 78% less CO<sub>2</sub> than diesel in order to produce the same amount of power (Sheehan *et al.* 1998). Also, the LCA analysis of alternative fuel for Australian heavy vehicles (Beer *et al.* 2002) found that pure biodiesel produces 40% less emission than petroleum diesel. However, this study had considered the production of biodiesel from canola, where the emission factor for canola production was based on international data. Therefore, further research needs to be carried out in order to ascertain the emission factor of canola oil production in order to incorporate this local data into the LCA analysis of biodiesel production in Australia. LPG, which is produced by extracting propane and butane from natural gas, can be considered as an alternative fuel to diesel fuel. Engines powered by LPG provide a reduction in life cycle GHG emissions of between 15 and 20% (Beer *et al.* 2000). However, only 18% of the natural gas reserve of Australia, which is about 130 years of consumption at the current rate, is economically recoverable in today's market (Diesendorf 2007). Therefore, natural gas, with a limited reserve as well as its higher demand from other sectors, such as domestic, industry and power, may not be a long-term substitute for diesel fuel.

Finally, in addition to LCA of GHG emissions, full economic, social and other environmental impacts (e.g. soil condition, air pollution, water quality) need to be taken into account in order to assess the sustainability of grain industries in south-western Australia and proposed GHG mitigation strategies. For example, other environmental impact categories need to be considered when assessing the use of biodiesel, as De Nocker *et al.* (1998) found that biodiesel use impacted more on soil and water acidification, eutrophication and radioactive waste type (i.e. other environmental impact categories) than use of diesel.

## Conclusions

- (1) LCA has been found to be a useful tool for calculating GHG emissions from the production and delivery of 1 tonne of wheat to port, and for identifying which production stages are responsible for these emissions. Including regional-specific data for N<sub>2</sub>O emissions from land improved the accuracy of the analysis.
- (2) The GHG emission during the production and delivery of 1 tonne of wheat to port was equivalent to 304 kg CO<sub>2</sub>, which was 38% less than the value calculated when using the IPCC emission factor for N<sub>2</sub>O.

- (3) The prefarm stage, which included environmental impact of the production of inputs, such as mining, processing and transportation to the point of use, accounted for the significant portion (45%) of the total global warming potential, followed by onfarm (44%) and postfarm (11%) stages.

- (4) The production of fertiliser accounted for a significant portion (35%) of the impact for prefarm and onfarm activities for wheat production, while GHG emissions from transportation were found to be predominant during the postfarm stage.

- (5) We recommend utilising regionally specific data for soil N<sub>2</sub>O emissions, rather than international default values, when assessing GHG from agricultural production systems. In addition, we suggest that approaches for decreasing emissions during prefarm and postfarm activities be further investigated in order to reduce the impact of Australian grain production on GHG emissions.

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## References

- Altham, W., Narayanaswamy, V., van Berkel, R. and McGregor, M. (2004) *Grains environmental data tool*. Technical Report for Grains Research and Development Corporation, Perth, Western Australia, Curtin University of Technology, 53 pp.
- Andersson, K. and Ohlsson, T. (1999) Life Cycle Assessment of Bread Produced on Different Scales. *Int. J. LCA*, **4** (1), 25–40.
- Barker-Reid, F., Gates, W.P., Wilson, K., Baigent, R., Galbally, I.E., Meyer, C.P., Weeks, I.A. and Eckard, R.J. (2005) Soil Nitrous Oxide Emission from Rainfed Wheat in SE Australia. In van Amsted, A. (ed). *Non-CO<sub>2</sub> Greenhouse Gases (NCGG-4)*. Utrecht, the Netherlands. 25 pp.
- Barton, L., Kiese, R., Gatter, D., Butterbach-Bahl, K., Buck, R., Hinz, C. and Murphy, D.V. (2008) Nitrous Oxide Emissions from a Cropped Soil in a Semi-Arid Climate. *Glob. Change Biol.*, **14**, 177–192.
- Beer, T., Grant, T., Brown, R., Edwards, J., Nelson, P., Watson, H. and Williams, D. (2000) *Life-cycle emissions analysis of*

- alternative fuels for heavy vehicles*. Report C/0411/1.1/F2, CSIRO Division of Atmospheric Research, Aspendale, Vic., xxi, 125 pp.
- Beer, T., Grant, T., Williams, D. and Watson, H. (2002) Fuel-Cycle Greenhouse Gas Emissions from Alternative Fuels in Australian Heavy Vehicles. *Atmos. Environ.*, **36**, 753–763.
- Bouwman, A.F. (1990) Exchange of Greenhouse Gases Between Terrestrial Ecosystems and the Atmosphere. In Bouwman, A.F. (ed). *Soils and the Greenhouse Effect*, pp. 61–127. John Wiley, Chichester.
- Braschkat, J., Braschkat, A., Quirin, M. and Reinhardt, G.A. (2003) Life cycle assessment of bread production – a comparison of eight different scenarios. Life cycle assessment in the agri-food sector. *Proceedings from the 4th International Conference*, 6–8 October, Denmark.
- CECP (Centre of Excellence in Cleaner Production). (2005) *Paddock Data (Inputs) Collected Through Data Sheets by Centre of Excellence in Cleaner Production*. Curtin University of Technology, Perth, WA.
- Commonwealth of Australia. (2007) Climate. Bureau of Meteorology, Commonwealth of Australia [online]. <http://www.bom.gov.au/climate> [accessed 9 October 2007].
- Crutzen, P.J. (1981) Atmospheric Chemical Processes of the Oxides of Nitrogen, Including Nitrous Oxide. In Delwiche, C.C. (ed). *Denitrification, Nitrification, and Atmospheric Nitrous Oxide*, pp. 17–44. John Wiley & Sons, New York.
- De Nocker, L., Spirinckx, C. and Torfs, R. (1998) Comparison of LCA and external-cost analysis for biodiesel and diesel. *2nd International Conference LCA in Agriculture, Agro-industry and Forestry*, 3–4 December, Brussels.
- Dentener, F., Derwent, R., Dlugokencky, E., Holland, E., Isaksen, I., Katima, J., Kirchhoff, V., Matson, P., Midgley, P. and Wang, M. (2001) Atmospheric Chemistry and Greenhouse Gases. In Houghton, J.T., Ding, Y. and Griggs, D.J. et al. (eds). *Climate change 2001: The Scientific Basis*. Contributions of Working Group 1 to the assessment report of the Intergovernmental Panel on climate change Cambridge University Press, Cambridge, UK and New York, NY, USA, 881 pp.
- Diesendorf, M. (2007) *Greenhouse Solutions with Sustainable Energy*. UNSW Press, NSW, Sydney.
- Ekvall, T. and Finnveden, G. (2001) Allocation in ISO 14041 – A Critical Review. *J. Cleaner Prod.*, **9**, 197–208.
- Gasol, C.M., Gabarell, X., Anton, A., Rigola, M., Carrasco, J., Ciria, P., Solano, M.L. and Rieradevall, J. (2007) Life Cycle Assessment of a *Brassica carinata* Cropping System in Southern Europe. *Biomass Bioenergy*, **31** (8), 543–555.
- Greadel, T. and Allenby, B. (2003a) An Introduction to Life Cycle Assessment. In Greadel, T. and Allenby, B. (eds). *Industrial Ecology*, 2nd edn. pp. 183–196. Pearson Education, Upper Saddle River, New Jersey, USA.
- Greadel, T. and Allenby, B. (2003b) The LCA Impact and Interpretation Stages. In Greadel, T. and Allenby, B. (eds). *Industrial Ecology*, 2nd edn. pp. 197–213. Pearson Education, Upper Saddle River, New Jersey, USA.
- Hamilton, S.K., Amanda, L., Kurzman, A.L., Clay Arango, C., Lixin Jin, L. and Robertson, G.P. (2007) Evidence for Carbon Sequestration by Agricultural Liming. *Global Biogeochem. Cycles*, **21**, 1–12.
- Harrison, P. and Pearce, F. (2000) *AAAS Atlas of Population and Environment*. University of California Press, Berkeley, USA, 204 pp.
- Heller, M.C. and Keoleian, G.A. (2000) *Life cycle-based sustainability indicators for assessment of the U.S. food system*. A Report of the Center for Sustainable Systems, Report No. CSS00-04, University of Michigan.
- Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., Linden, P.J., Dai, X., Maskell, K. and Johnson, C.A. (2001) *Climate Change 2001: The scientific basis*. Contributions of Working Group 1 to the Assessment report of the Intergovernmental Panel on climate change, Cambridge University Press, Cambridge.
- IPCC (2006). *N<sub>2</sub>O emissions from managed soils, and CO<sub>2</sub> emissions from lime and urea application*. Chapter 11, IPCC Guidelines for National Greenhouse Gas Inventories, 4, 11.1–11.54.
- ISO (1997) *Environmental Management – Life Cycle Assessment – Principles and Framework, ISO 14040*. International Organization for Standardization (ISO), Geneva.
- Kaltschmitt, M., Reinhardt, G.A. and Stelzer, T. (1997) Life Cycle Analysis of Biofuels Under Different Environmental Aspects. *Biomass Bioenergy*, **12** (2), 121–134.
- Leng, R., Wang, C., Zhang, C., Dai, D. and Pu, G. (2008) Life Cycle Inventory and Energy Analysis of Cassava-Based Fuel Ethanol in China. *J. Cleaner Prod.*, **16** (3), 374–384.
- Mosier, A.R., Duxbury, J.M., Freney, J.R., Heinemeyer, O. and Minami, K. (1998) Assessing and Mitigating N<sub>2</sub>O Emissions from Agricultural Soils. *Clim. Change*, **40**, 7–38.
- Nemecek, T., Heil, A., Huguenin, O., Meier, S., Erzinger, S., Blaser, S., Dux, D. and Zimmermann, A. (2004) *Life cycle inventories of agricultural production systems*. Final Report 'Ecoinvent 2000', Vol. 15, Swiss Centre for LCI, FAL & FAT. Dübendorf, CH.
- RMIT (Royal Melbourne Institute of Technology) *Australian LCA database 2005*. Centre for Design, RMIT, Vic.
- Robertson, G.P., Paul, E.A. and Harwood, R.R. (2000) Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere. *Science*, **289**, 1922–1925.
- Schumacher, K. and Sathaye, J. (1999) *India's fertiliser industry: productivity and energy efficiency*. This work was prepared for the Environmental Science Division, Office of Biological and Environmental Research (OBER), Office of Energy Research, U.S. Department of Energy, under Contract No. DE-AC03-76SF00098.
- Sheehan, J., Camobreco, V., Duffield, J., Graboski, M. and Shapouri, H. (1998) *Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus*. NREL/SR-580-24089 UC Category 1503, National Renewable Energy Laboratory, Colorado.

- Simapro. (2006) Version 7, PRé Consultants, the Netherlands.
- Stehfest, E. and Bouwman, L. (2006) N<sub>2</sub>O and NO Emission from Agricultural Fields and Soils Under Natural Vegetation: Summarizing Available Measurement Data and Modeling of Global Annual Emissions. *Nutr. Cycl. Agroecosyst.*, **74**, 207–228.
- Suh, S. (2004) *Material and Energy Flows in Industry and Ecosystem Network*. Centre for Environmental Science, University of Leiden, the Netherlands.
- Suwanwaree, P. and Robertson, G.P. (2005) Methane Oxidation in Forest, Successional, and No-Till Agricultural Ecosystems: Effects of Nitrogen and Soil Disturbance. *Am. J. Soil Sci. Soc.*, **69**, 1722–1729.
- West, T.O. and McBride, A.C. (2005) The Contribution of Agricultural Lime to Carbon Dioxide Emissions in the United States: Dissolution, Transport, and Net Emissions. *Agric. Ecosyst. Environ.*, **108**, 145–154.
- World Meteorological Organization. (2006) *The state of greenhouse gases in the atmosphere using global observations up to December 2004*. World Meteorological Organization Greenhouse Gas Bulletin.