Journal of Cleaner Production 135 (2016) 1256–1266

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

An international comparison of agricultural nitrous oxide emissions

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ARTICLE INFO

Article history:
Received 18 March 2016
Received in revised form
6 July 2016
Accepted 6 July 2016
Available online 9 July 2016

Keywords:
Agriculture
Nitrous oxide emissions
Synthetic N fertilisers
Farm manure
Crop residue

ABSTRACT

Agriculture is a major source of global greenhouse gas emissions, accounting for approximately 14–17% of global anthropogenic emissions. Among others, nitrous oxide emissions from synthetic fertilisers, manure applications and crop residues left on farms account for over 40% of total agricultural emissions. This research aims to analyse trends and magnitudes of nitrous oxide emissions from these three sources over a 52 year period (1961–2012) in seven major crop producing countries including: (1) three developed countries (Australia, Canada and USA); and (2) four developing countries (Argentina, Brazil, China and India). Annual emissions and other required data for the study were collected from Food and Agriculture Organisation and World Bank sources. Among these seven countries, Australia appears to perform well in terms of maintaining relatively lower total emissions from the three sources and increasing crop production indices. China and India ranked well in terms of crop production indices but had higher emissions. The reasons why such differences between the countries exist and what lessons other countries can learn from the Australian experience are discussed. This is critical in a low-carbon economy where an environmentally-friendly agricultural production system is rewarded.

1. Introduction

Agriculture is one of the major sources of greenhouse gas (GHG) emissions, accounting for about 5.4–5.8 $GtCO_2e$ (gigatonne of carbon dioxide equivalent) in 2010, approximately 11% of total anthropogenic emissions (Tubiello et al., 2013). This amount relates to direct sources only. If emissions from the production, packaging, storage and transportation of agricultural inputs and the processing and transportation of farm products are considered, a further 3–6% of global emissions (Vermuelen et al., 2012) are accounted for. When considering direct agricultural emissions, 38% is attributed to nitrous oxide (N_2O) from soils, 32% to methane (CH_4) from ruminants, 12% to biomass burning, 11% to CH_4 from rice production and 7% to manure management (Bellarby et al., 2008). With increasing use of energy intensive farm machinery and farm inputs, agriculture related emissions are increasing rapidly (Maraseni et al., 2007; Maraseni and Cockfield, 2011a,b; Mushtaq et al., 2013). For example, from 1990 to 2005, global agriculture emissions increased by 14%, increasing at an average rate of 49 $MtCO_2e$/yr (US-EPA, 2006). Moreover, in order to feed a growing global population, crop land expansion is going on. This is the largest driver of forest loss and, thereby, source of biomass carbon and soil carbon released into the atmosphere (FAO, 2015). Therefore, meeting the proposed 2 °C climate stabilisation target is not possible without reducing agricultural emissions.

Nitrous oxide from synthetic fertilisers, manure applications and crop residues left on farms account for over 40% of total agricultural emissions alone (WRI, 2014). Among the synthetic fertilisers, nitrogen (N) fertilisers are major contributors of global emissions as they, during nitrification and denitrification processes, produce N_2O which has 298 times greater global warming potential than carbon dioxide (CO_2; IPCC, 2007; Yan et al., 2015). Until the early 1900s, legume-based rotational cropping systems were very popular for fixing N and making it available to subsequent non-leguminous crops (Barton et al., 2014). As a result, the use of N-fertiliser and related GHG emissions were lower. This cropping system also serves to regenerate soil fertility (Dhakal and Scanlan, 2015), increase soil carbon levels (Paul et al., 2002), help maintain manageable pest populations and retard pest evolution (Crews and Peoples, 2004), reduce weed seed banks (Liebman and Dyck, 1993)

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http://dx.doi.org/10.1016/j.jclepro.2016.07.035
0959-6526/

and crop loss to some insects and diseases. Furthermore, some legumes have the capacity to prevent N leaching by producing nitrification inhibitors (Subbarao et al., 2007).

With the invention of the Haber-Bosch process of synthesising ammonia during the early 1900s, farmers around the world started to replace legume-based nutrient rotational cropping systems with synthetic N fertilisers (Maraseni, 2015). The rapid adoption of synthetic N fertilisers is reflected in global N fertiliser and pesticide consumption. For example, global use of N fertilisers in 1999 was about 23 times higher compared to the 1950s (Smil, 1999). Similarly, along with the reduction of legume based cropping systems, global use of agricultural pesticides increased from a value of US$20.5 billion in 1993 by an average of 3% per year to US$27.5 billion in 2003 (Vlek et al., 2003). GHG emission factors per unit of pesticide production are over seven times higher than that of N fertiliser production (Maraseni et al., 2007). Packaging, transportation, storage and application of these chemicals need more energy and thereby emit more GHG emissions.

Setting aside these issues, this research aims to analyse the trends and magnitudes of N_2O emissions from arable land due to use of synthetic N fertilisers, farm manure and retention of crop residues on the farms in seven major agriculture producing countries, including three developed countries (Australia, Canada and USA) and four developing countries (Argentina, Brazil, China and India (Fig. 1). Collectively these developed and developing countries emit about 11.2% and 37.6% of world total agricultural emissions, respectively (FAOSTAT, 2015).

Inclusion of developing countries is very important for several reasons. When climate change policies were initially developed in the early 1990s, developing countries were responsible for approximately 40% of total anthropogenic GHG emissions. Nowadays, they are responsible for about 60% of total emissions (Maraseni et al., 2009; UNEP, 2013). The share is even higher in the agriculture sector where, in 2005, developing countries were responsible for 74% of global agricultural emissions whereas developed countries were responsible for 26% (Smith et al., 2007). The proportional contribution of agricultural emissions for developing countries has been increasing in recent years, mainly due to consumption of farm inputs as developing countries need to feed growing populations with limited farming areas (Tubiello et al., 2013). Developing countries are also more vulnerable to climate change mainly due to their geographical location, poor adaptive capacity and lack of financial resources for adaptation (Stern, 2006). The challenges for climate change adaptation and mitigation in developing countries are massive, especially for those that are least financially capable (Stern, 2006). As a result, the Paris Agreement has committed (non-bindingly) to assist, with financial support, poor developing countries in their mitigation and adaptation efforts (United Nations, 2015).

2. A brief snapshot of global emissions and selected countries' agriculture and soil emissions

According to the IPCC (2014), the rate of increase in anthropogenic greenhouse gas (GHG) emissions in the last decade (2000–2010) was much greater (2.2%/yr) than that of the previous 30 years (1.3%/yr). In 2010, there were approximately 50.1 $GtCO_2e$ GHG emissions from anthropogenic sources. This amount was already 14% higher than the proposed limit (44 $GtCO_2e$/yr) to meet the 2 °C climate target by 2020 (UNEP, 2013). Realising the catastrophic threat posed by climate change, the 2015 Paris Agreement, under the United Nations Framework Convention on Climate Change (UNFCCC) and backed by 195 countries, aims to limit the increase in global average temperatures to below 2 °C and, where/if possible, limit it to 1.5 °C (UNFCCC, 2015; United Nations, 2015). However, the current annual fall in carbon intensity (carbon

Fig. 1. World map with selected seven countries.

emissions per unit of gross domestic product) of 1.3% is not enough; an annual fall rate of 6.2% is required to meet the 2 °C climate stabilisation target (PWC, 2015).

As noted, agriculture is one of the major sources of global GHG emissions. Collectively, the seven countries selected for this assessment account for 52.4% of world total soil emissions and 49.1% of world total agricultural emissions (Table 1). Amongst these, China, India, Brazil and USA are major contributors. China alone accounts for 21.2% of world total soil emissions and 15.5% of world total agricultural emissions, whereas these values for India are 10.5% and 12.2%, respectively. These figures suggest that China is not only the world's largest GHG emitting country from all sectors (Maraseni, 2013; Maraseni et al., 2015), but is also the largest GHG emitting country from the agriculture sector (FAOSTAT, 2015). Surprisingly, India is only a small contributor of global emissions, but second largest in the agriculture sector (FAOSTAT, 2015).

Agricultural soil emissions for these countries contribute to a significant proportion of national agricultural emissions. For example, Canada's agricultural soil emissions (34,588.2 $GgCO_2e$) account for over 60% of national agricultural emissions, whereas China (447,781.4 $GgCO_2e$) and USA (169,299 $GgCO_2e$) account for over 53% and 47%, respectively. Australia's share (41,357.7 $GgCO_2e$) is lowest among the seven countries as the majority of its agricultural emissions come from the livestock sector (DCCEE, 2012).

3. Methods

This research uses time series data over a 52 year period (1961–2012) for the comparison of trends and magnitudes of N_2O emissions from arable lands due to the use of synthetic N fertilisers, farm manure and retention of crop residues on farms of the seven major agriculture producing countries. According to the Food and Agriculture Organisation (FAO), arable land includes land under temporary crops, temporary meadows for mowing or for pasture, land under market or kitchen gardens and also land temporarily fallow (FAOSTAT, 2015); hence, the area of arable land may change over time. From data available from the World Bank (2015), the area of arable land for the countries investigated in this study, with the exception of the USA, increased over the 52-year period. The highest estimated increase in arable land was in Brazil (228.3%), followed by Argentina (113.8%) and Australia (56.1%); whereas, in the USA, there was a decrease of 14.1%. This was mainly because of the conversion of arable land into permanent cropland—land cultivated with crops that occupy the land for long periods and need not be replanted after each harvest (FAOSTAT, 2015). For example, in 1961, there were 1,879,000 ha of permanent cropland in the USA which, by 2012, had increased to 2,600,000 ha, an increase of 38.37% (FAOSTAT, 2015). Because of the changing nature of arable land (World Bank, 2015) emissions were compared on a per hectare basis.

Yearly data of N_2O emissions due to use of synthetic N fertilisers, farm manure and crop residues for the 52-year period were taken from FAOSTAT (2015). The data for each year were divided by the area of arable land for that year to provide an estimate of average per hectare emissions. FAO emissions estimates were calculated using Tier 1 methods, following the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories. This database also contributed to the IPCC WGIII 5th Assessment Report (Tubiello et al., 2015).

In the Tier 1 method, default emission factors for synthetic N fertilisers, farm manure and crop residues most appropriate for the selected countries are used. These emission factors have been drawn from previous studies and are organised by region for ease of use. Technical details of these data and relevant computational steps are given in the Methodology and Quality Information section of the metadata (FAOSTAT, 2015). The FAOSTAT database is useful for: (1) quality control and quality assurance procedures for GHG inventories; and (2) updating global and regional trends in GHG emissions and, thereby, benchmarking and making global comparisons (Tubiello et al., 2015); and (3) member countries to assess and report their emissions (FAOSTAT, 2015). In terms of spatial and temporal resolutions, Tier 1 data are not as accurate as Tier 2 and Tier 3 data but these higher Tiers require more resources for collecting country and region specific database (Tubiello et al., 2015).

In summary, in the FAOSTAT database, GHG emissions from synthetic N fertilisers, farm manure and crop residues consist of direct N_2O emissions produced by microbial processes of nitrification and de-nitrification of nitrogenous compounds and also indirect N_2O emissions due to volatilisation/re-deposition and leaching processes (IPCC, 2006; Volume 4; Tubiello et al., 2015). Therefore, this research includes both direct and indirect N_2O emissions from different processes.

Along with the N_2O emission from different sources, crop production indices (PIN) of selected countries are compared. PIN values show the relative level of the aggregate volume of crop production for each year in comparison with the base period 2004–2006 (FAOSTAT, 2015). They are based on the sum of price-weighted quantities of different commodities produced after deductions of quantities used as seed weighted in a similar manner (FAOSTAT, 2015).

4. Results and discussions

4.1. Emissions of N_2O from arable land due to use of synthetic N fertilisers

Fig. 2 presents the trends and magnitudes of average N_2O emissions from arable land due to the use of synthetic N fertilisers

Table 1
Share of world total soil emissions and agriculture emissions from seven selected countries (adopted from FAOSTAT, 2015).

Country	Agriculture soil emissions			Agriculture emissions	
	Agriculture soil emissions ($GgCO_2e$)	% of national agriculture emissions	% of world total soil emission	Total agriculture emissions ($GgCO_2e$)	% of world total agriculture emissions
Argentina	39725.9	37.2	1.9	106733.5	2.0
Australia	41357.7	21.7	2.0	190566.4	3.5
Brazil	153518.9	34.5	7.3	444414.4	8.3
Canada	34588.2	60.2	1.6	57471.3	1.1
China, mainland	447781.4	53.8	21.2	831557.4	15.5
India	222041.7	33.7	10.5	658823.2	12.2
USA	169299.0	47.8	8.0	353886.3	6.6
World total	2114177.0	39.3	100	5381510.2	100

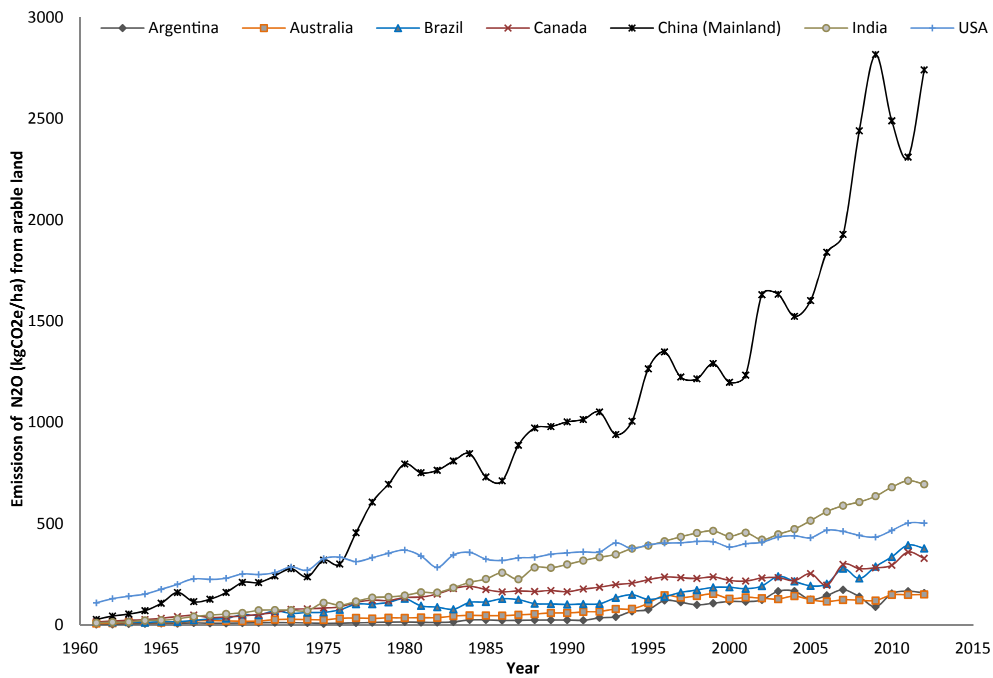

Fig. 2. Average emissions of N_2O ($kgCO_2e/ha$) from arable lands due to use of synthetic N fertilizers in selected countries between 1960 and 2012 using FAOSTAT data.

in the seven countries. In 1961, synthetic N fertiliser related emissions was highest in the USA (109 $kgCO_2e/ha$) followed by China (27.2 $kgCO_2/ha$) and Brazil (16.1 $kgCO_2e/ha$). However, in 2012, China (2740.8 $kgCO_2e/ha$) and India (694.6 $kgCO_2e/ha$) both overtook the USA (503.2 $kgCO_2e/ha$), whilst Australia had the lowest (150.6 $kgCO_2e/ha$) emissions amongst these countries. This is mainly because of the higher percentage of permanent pastures/rangelands in Australia which, in comparison to annual crops such as peanut, maize, barley, wheat, chickpeas and durum, are less fertilised (Maraseni, 2007; Maraseni and Cockfield, 2011a,b).

During the 52 year period, synthetic N fertiliser related emissions in China, India and Argentina increased by a factor of 100, 67 and 54, respectively. The lowest incremental rate was in the USA (4.6 times), mainly because of its high starting base (109.2 $kgCO_2e/ha$ in 1961). However, the USA (503.2 $kgCO_2e$) was still among the top three emitters in 2012. China's average emissions in 1961 were not as high as the USA, but have been rising exponentially since 1975. India had slow and steady growth until 1982 (284.6 $kgCO_2e/ha$ in 1982) but has since grown rapidly. There are two possible reasons for such growth in China and India. Firstly, both China and India have populations exceeding 1.3 billion, representing 19.42% and 17.84% of the world population, respectively (Burck et al., 2014). Among their populations, 217 million people in India and 185 million people in China are food insecure with, ironically, many of them being agricultural producers (IFAD, WFP and FAO, 2012). Nitrogen fertilisers are heavily relied upon in these countries as a means of increasing productivity (International Fertilizer Industry Association, 2015).

Secondly, as noted, arable land includes land under temporary crops (FAOSTAT, 2015). Although temporary cropland data are not available for India and China, most arable land is classified as under temporary crops (FAOSTAT, 2015); whereas, in other countries such as USA, Canada and Argentina, temporary croplands account for some 82.3%, 79.6% and 78.8% of the arable land, respectively (Table 2). Australia is an exception, with only about 56% of the arable land classified as temporary cropland. As noted, temporary crops need more frequent and higher amount of N fertilisers than other crops. Therefore, it is likely that China and India have higher amounts of N fertiliser related emissions.

In addition to N fertilisers, N_2O emissions from soil also come from a variety of sources such as manure applied to soils, manure left on pastures, crop-residues left on farms, burning of crop residues, burning of savanna etc. It would be interesting to see how the proportion of synthetic N fertilisers related emissions have been changed overtime.

In 1961, synthetic N fertiliser related emissions in the USA contributed about 23.2% of the total N_2O emissions from the agricultural sector; whereas, in Canada and China, their contribution was 8.29% and 5.4%, respectively (Fig. 3). Values for Argentina, Australia and Brazil were <1%. From 1961 to 2012, the proportion of synthetic N fertiliser related emissions increased in all countries (Fig. 3); for example, increases of 81.8 times in Argentina, 26.2 times in Australia, 18 times in Brazil, 17.8 times in India and 12 times in China are evident. However in 2012, in terms of absolute percentage, China (64.83% of total N_2O emissions from soils) and India (48.97% of total N_2O emissions from soils) overtook all other countries. In both of these countries, the proportional contribution of N_2O emissions from N fertilisers has increased steadily since 1961 but, in China during the latter parts of the 1970s and 2000s, the increment was very high (International Fertilizer Industry Association, 2009). The contributions of synthetic N fertiliser related emissions for Argentina, Australia and Brazil in 2012 were less than 20%. In these countries, significant proportions of soil N_2O emissions came from livestock urine and dung, with Australia also having soil N_2O emissions from savanna burning (DCCEE, 2012).

4.2. Emissions of N_2O from arable lands due to use of manure

Application of manure on farms is a centuries-old practice, primarily for increasing productivity of the soil system. However, manure contains N nutrients and therefore is also a source of N_2O emissions. In 1961, Brazil had the highest average N_2O emissions (161.4 $kgCO_2e/ha$) from farm manure followed by China (90.5 $kgCO_2e/ha$) and the USA (78.9 $kgCO_2e/ha$). In 2012, China (367.4

Table 2
Temporary and arable crop area (in 000'ha) in 2006*.

	Argentina	Australia	Brazil	Canada	China (Mainland)	India	USA
Temporary crops land	27454	26742	54527	35912	NA	NA	132037
Arable land	34854	47715	69538	45112	108700	158662	160441
% of temporary crop land As compared to arable land	78.77	56.05	78.41	79.61	NA	NA	82.30

Note: We tried our best to collect time series data of temporary cropland but they are not available and year 2006 data are compared.

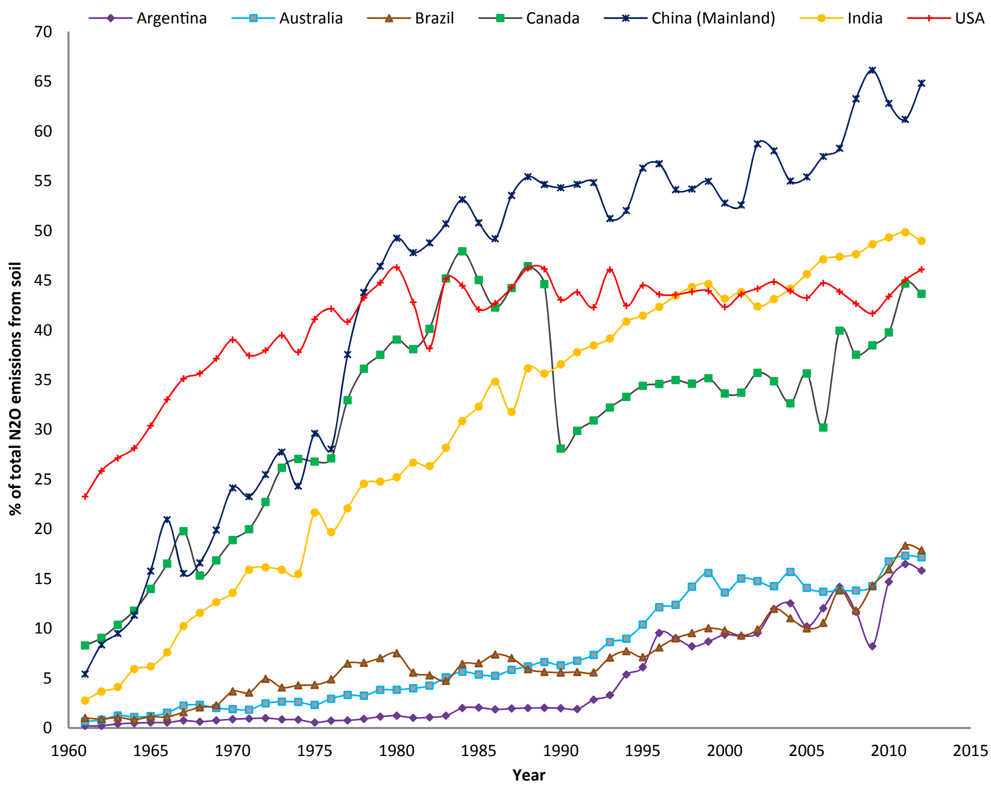

Fig. 3. Percentage of total N_2O emissions from agriculture soils contributed by synthetic N-fertilisers in selected countries between 1960 and 2012 using FAOSTAT data.

kgCO_2e/ha) overtook Brazil (143.4 kgCO_2e/ha) for the highest manure related N_2O emissions (Fig. 4).

From 1961 to 2012, farm manure related emissions in China and India increased by 306% and 86.3%, respectively; whereas, in Argentina and Brazil, they decreased by 51.5% and 11.2%, respectively. In India, the incremental rate of increase was steady throughout the study period, but in China, while the annual increment was large from the beginning of the period, it increased exponentially after 1998.

The high increments in China and India are likely associated with two main reasons: (1) many farmers in these countries are small-holders and livestock is an integral part of their cropping system, contributing additional manure on farms; and (2) in recent years, there has been an increasing demand for organic products with some farmers changing their practices in response (Patkar et al., 2012; Yadav, 2012). The sharp decline of farm manure related emissions in Argentina is probably due to a sharp increases in N fertiliser application rates; as discussed earlier, from 1961 to 2012, N fertiliser related N2O emissions in Argentina increased by over 54 times (Fig. 4).

4.3. Emissions of N_2O from arable lands due to crop residues

Leaving crop residues on the farm is another age-old practice utilised all around the world. These residues are a source of N_2O emissions as they contain the element N. In 1961, China had the highest average N_2O emissions (111.9 kgCO_2e/ha) from this source, followed by the USA (68.2 kgCO_2e/ha) and Brazil (67.1 kgCO_2e/ha), whereas Australia had the lowest (28 kgCO_2e/ha) (Fig. 5). In 2012, China (329.5 kgCO_2e/ha) and the USA (166.8 kgCO_2e/ha) maintained their first and second positions, but Brazil (141.6 kgCO_2e/ha) was overtaken by India (155 kgCO_2e/ha) for third.

From 1961 to 2012, the highest increase in N_2O emissions from crop residues was estimated to be for China (194.5%) followed by Australia (152.3%), the USA (144.5%), Canada (135.6%) and Argentina (134.5%). However, during this period, crop residue related N_2O emissions had increased in all countries. This was probably due to two main reasons: (1) farmers may believe that residues are a viable source of soil organic carbon; and (2) the increasing practice of zero/minimum tillage systems along with stubble retention (UNEP, 2013). Both of these practices increase crop residues on farms and thereby increase related emissions.

Conventional intensive cultivation systems result in a loss of soil carbon which adversely affects soil fertility, soil water holding capacity and also plant-available water capacity (Chan et al., 2009; Pattanayak et al., 2005). Zero tillage, along with stubble retention, may increase productivity, profitability and sustainability of the soil system. In addition, this practice may improve crop yields, reduce

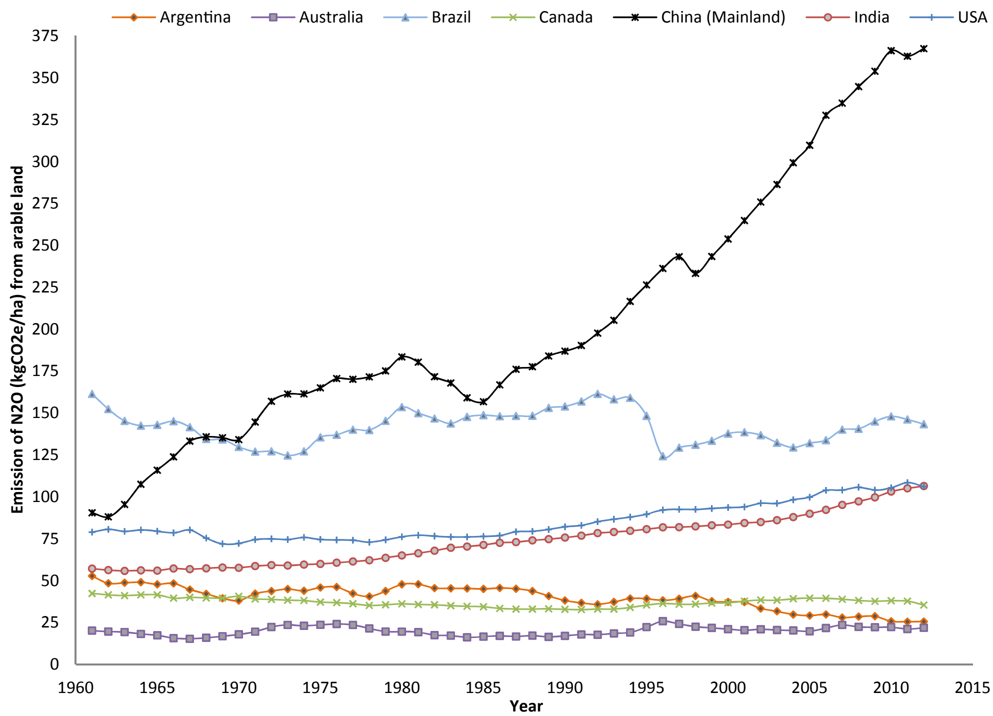

Fig. 4. Average emissions of N_2O ($kgCO_2e/ha$) from arable land due to use of manure in selected countries between 1960 and 2012 using FAOSTAT data.

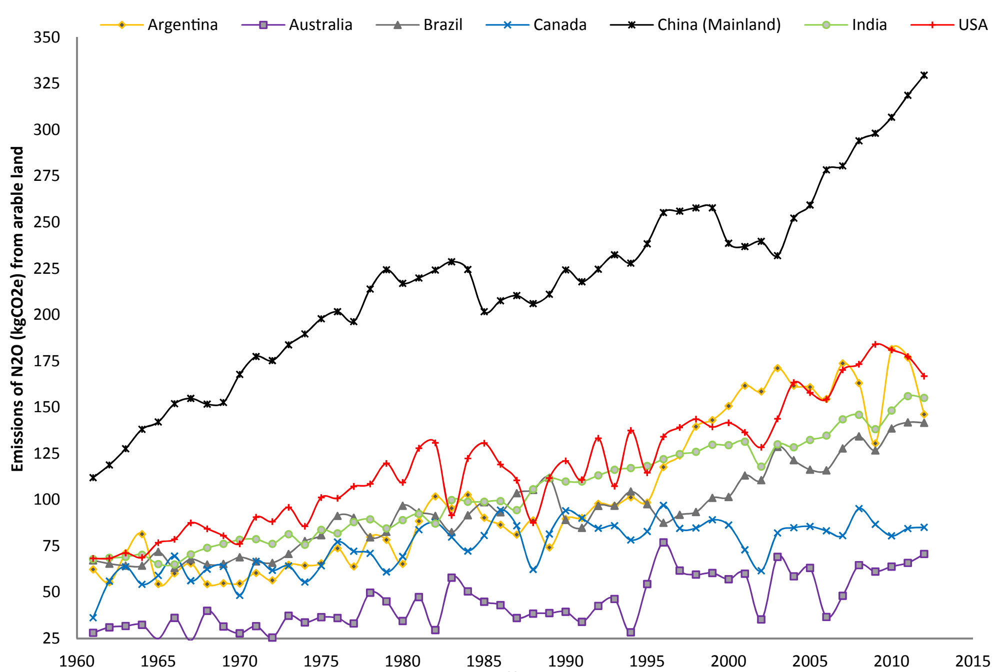

Fig. 5. Average emissions of N_2O ($kgCO_2e/ha$) from arable land due to crop residues in selected countries between 1960 and 2012 using FAOSTAT data.

labor and fuel costs, decrease GHG emissions due to reduction of fuel usage (Llewellyn and D'emden, 2010) and also reduce soil carbon losses (Chan et al., 2009). Therefore, farmers increasingly prefer these practices.

Whether zero till also increases N_2O emissions is a contentious issue. Some scholars report that it may increase such emissions (Dalal et al., 2003; Maraseni and Cockfield, 2011a,b) whilst others suggest it may not (Smith et al., 2008; UNEP, 2013). Increased N_2O emissions resulting from zero tillage systems which include stubble retention are likely as stubble is a source of carbon and energy for heterotrophic denitrifying organisms (Dorland and Beauchamp, 1991; Iqbal, 1992). This is supported by wheat and sugarcane soil research in Australia (Dalal et al., 2003). In our results, as noted for China, there is a positive relationship between the increasing trend of zero tillage along with stubble retention and N_2O emissions from the residues. For example, the area under zero tillage systems in China increased by two million hectares from 2000 to 2007/08 (Smith et al., 2008; UNEP, 2013). During the same period, crop residue related emissions increased by 90.9 $kgCO_2e$/ha. However, as N_2O emissions may also be affected by several other factors such as climatic and edaphic conditions, further research is required to determine whether the observed positive trends are due to causation or simply a correlation.

There are several studies that have examined how carbon footprints can be reduced from cropping systems, such as: (1) including legume crops in the farming system to reduce both N_2O and soil carbon emissions (Paul et al., 2002; Barton et al., 2014); (2) diversification of crop rotation to reduce overall carbon footprints (Yang et al., 2014); (3) keeping crop residue and application of manure on farms to increase soil carbon levels (Peterson et al., 2013; Knudsen et al., 2014; Mukul et al., 2016); (4) application of biochar into soil to reduce nutrient leaching and N_2O emissions (Pudasaini et al., 2012); and (4) maintaining soil moisture levels below certain percentage to reduce the amount of direct and indirect N_2O emissions (Castanheira and Freire, 2013). However, these are outside the scope of this paper and their impacts are, therefore, not considered.

4.4. Crop production indices (PIN) and their relationship with N_2O emissions from different sources

A time series analysis of PIN was undertaken to enable a comparison across crops and countries given different countries produce different varieties of crops in different proportions. Crop PIN values quantify where countries were before 2004–2006 and how they have progressed since this period (FAOSTAT, 2015). The relationship between crop PIN and N_2O emissions from different sources gives an indication about farm efficiency. These emissions can be considered as proxies of farm inputs.

In 1961, the USA had the highest crop PIN (43.9), followed by India (35.8) and Canada (26.2), while Brazil had the lowest (23.6) (Fig. 6 and Table 3). In 2012, Australia topped the list (139.9), followed by India (136.0) and China (130.7); whereas the USA had fallen to the lowest (100.9). From 1961 to 2012, crop PIN in China had increased by 6.9 times and in both Australia and Brazil by 5.5 times, whereas the lowest increment was observed in the USA (2.3 times).

The lowest incremental rate and crop PIN for 2012 does not mean that the USA had not done well. The USA had a very good starting base in 1961 and before 2004–2006. However one thing is certain; it has not progressed lately. On the other hand, Australia, China and India have progressed significantly since the 2004–2006 period; although, conversely, China's high incremental increase was mainly due to its low starting base.

In order to discuss the relationship between crop PIN and farm inputs, N_2O emissions from different sources were considered as a proxy of farm inputs. Regression models show that, in all countries, N fertilisers explained over 85% of variation in crop PIN. In China and India, where livestock is an integral part of farming systems, manure explained over 94% of the total variation in crop PIN. In the USA, where zero tillage along with stubble retention has been a common practice, crop residue left on farms explained the highest percentage (95.7%) of total variation in crop PIN. For example, in the USA, the area under zero tillage increased by approximately 26.5 million hectares between 1974 and 2007/08 (UNEP, 2013).

Among these seven countries, Australia seems have been most successful in maintaining relatively low total emissions from all three sources while increasing crop PIN. China and India also performed well in terms of crop PIN but with the cost of higher emissions (Table 3). For example, China and India's total average emissions from these three sources were 229.6 $kgCO_2$/ha and 135.2 $kgCO_2$/ha, respectively, in 1961; this had increased to 3437.7 $kgCO_2$/ha and 956.0 $kgCO_2$/ha, respectively, in 2012—an increase of 1397.3% and 607.1%, respectively. In the case of Australia, the total emissions from these sources in 1961 were 55.6 $kgCO_2$/ha and this had increased to 243.1 $kgCO_2$/ha in 2012, an increase of only 337.2%.

The higher productivity in the Australian cropping sector is mainly due to massive structural changes, reduction in incentives and subsidies, invention of new technologies and management practices, and concentrated industry production (Gray et al., 2014). The adoption of conservation tillage practices combined with the use of new crop varieties increased crop yields throughout the 1990s (Dunlop et al., 2004). Similarly, the level of producer support in Australian agriculture decreased from 10% in 1986 to 3% in 2012 (OECD, 2013). Price subsidies, which were previously approximately 87% of PSE, also declined to 6% by 2012 (Gray et al., 2014). Market price support to agricultural products is no longer provided (OECD, 2013). These policy measures forced farmers and agricultural industries to rapidly innovate. The number of farms decreased and average farm size increased and, due to the economies of scale and concentrated production, large farms became more efficient and productive. Now the top 20% of farms in Australia account for >50% of total output (Sheng et al., 2014).

Compared to Australia, other countries, particularly those in North America and Europe, provide considerable assistance to their agricultural sectors (Sheng et al., 2015). Higher subsidies in these countries artificially drive down global crop prices. If these subsidies were instead used for innovation, this would have a more sustainable outcome (Clay, 2013).

In China and India, as noted, many farmers are small-holders (Patkar et al., 2012) and suffer poor economies of scale. Despite this, crop yields have improved significantly in these countries. For example, in India from 1961 to 2012, per hectare yield of rice and barley increased by 2.4 times, maize by 2.7 times, sorghum by 2.2 times and potatoes by 3 times. In China, the yield of rice and barley increased by 3.2 times, maize by 5 times, sorghum by 4.4 times and potatoes by 1.7 times (FAOSTAT, 2015).

Increased yield can come from increased inputs and/or increased efficiency of inputs used (productivity). In China, productivity contributed only about half of the observed yield growth while the other half was due to increased inputs, especially fertilisers (Wang et al., 2013). Research and development are prime factors linked to increasing crop productivity. Spending money on research and development in the agricultural sector in China is poor. For example, in 2000, agricultural research intensity (proportion of agricultural research expenditure and agricultural gross domestic product) in China was 0.38%, whereas averages for developing and developed countries were 0.55% and 2.35%, respectively (Chen and Zhang, 2010). Therefore, China needs to invest in comprehensive research into increasing the efficiency of fertiliser use and yield improvements so that a win-win solution can be produced.

4.5. GHG emissions from other sources

So far, N_2O emissions from different sources for arable land have been discussed. However, some countries may have higher N_2O emissions from these sources, but lower agriculture methane (CH_4) and forest and land use change (LUCF) related emissions. In this section, emissions from these two additional sources are discussed. Agriculture CH_4 emissions include emissions from animals, animal waste, rice production, agricultural waste burning and savannah burning; whereas LUCF related emissions include net GHG emissions due to forest and land-use change activities (World Bank,

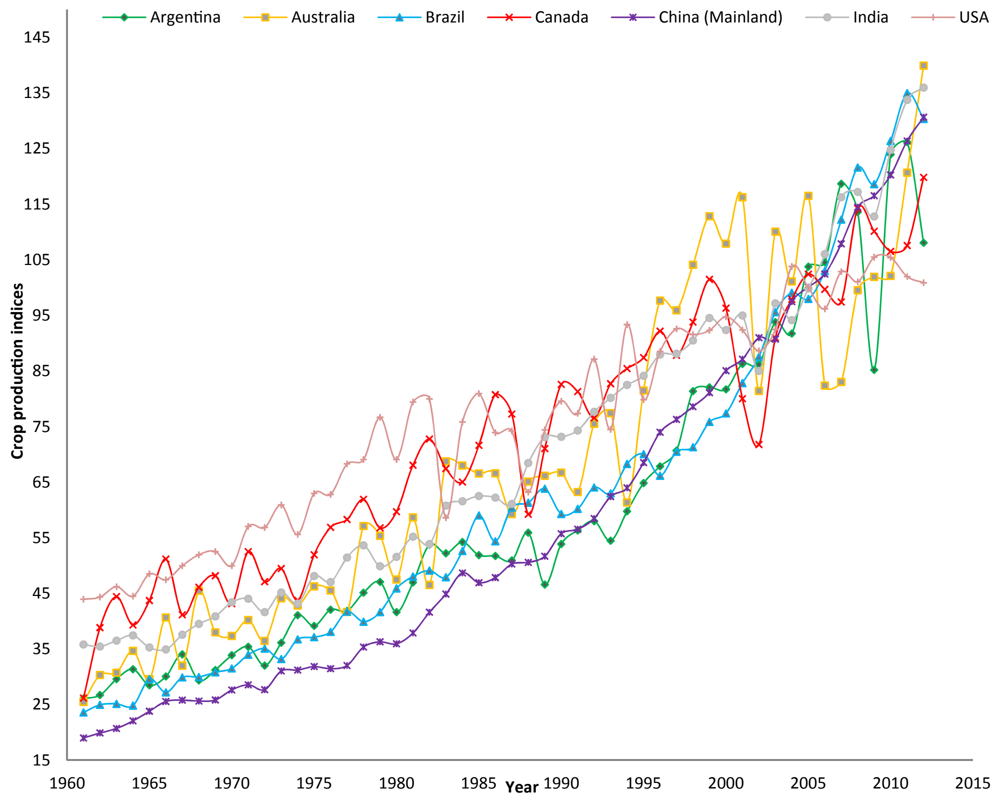

Fig. 6. Crop production indices (PIN) of selected countries between 1960 and 2012 using FAOSTAT data.

Table 3
Average per hectare N_2O emissions from arable land from different sources in 1961 and 2012 and the percentage change during that period; last three rows show crops PIN.

		Argentina	Australia	Brazil	Canada	China (Mainland)	India	USA
Use of N fertiliser	1961 ($kgCO_2e/ha$)	2.9	7.5	16.1	15.5	27.2	10.3	109.2
	2012 ($kgCO_2e/ha$)	158.0	150.6	377.9	328.9	2740.8	694.6	503.2
	Change % (1961–2012)	5326.8	1910.8	2251.8	2016.0	9961.5	6612.4	360.6
Use of manure	1961 ($kgCO_2e/ha$)	52.7	20.1	161.4	42.3	90.5	57.1	78.9
	2012 ($kgCO_2e/ha$)	25.6	21.9	143.4	35.4	367.4	106.4	106.1
	Change % (1961–2012)	−51.5	8.7	−11.2	−16.4	306.0	86.3	34.5
Crops residues on farm	1961 ($kgCO_2e/ha$)	62.2	28.0	67.1	36.1	111.9	67.8	68.2
	2012 ($kgCO_2e/ha$)	146.1	70.6	141.6	85.0	329.5	155.0	166.8
	Change % (1961–2012)	134.8	152.3	110.9	135.6	194.5	128.6	144.5
Sum of three sources	1961 ($kgCO_2e/ha$)	117.8	55.6	244.6	93.9	229.6	135.2	256.3
	2012 ($kgCO_2e/ha$)	329.7	243.1	662.9	449.3	3437.7	956.0	776.1
	Change % (1961–2012)	179.9	337.2	171.0	378.5	1397.3	607.1	202.8
Crop PIN	1961 ($kgCO_2e/ha$)	26.1	25.5	23.6	26.2	19.0	35.8	43.9
	2012 ($kgCO_2e/ha$)	108.1	139.9	130.4	119.8	130.7	136.0	100.9
	Change % (1961–2012)	314.2	449.1	452.8	358.2	588.0	279.9	129.6

2016). For developed countries, these data are drawn from the annual GHG inventories submitted to the UNFCCC and, for developing countries, such data are drawn from the most recently submitted National Communication (World Bank, 2016).

Agricultural CH_4 emissions data are available for all countries from 1970 to 2008; but net GHG emissions by LUCF activities are available only for developed countries for the period of 1990–2009 (World Bank, 2016). In 1970, agricultural CH_4 emissions were highest in China, followed by India and the USA (Table 4). By 2008, the patterns had remained the same, with China and India still surpassing USA. However, during the 38 year period, agricultural CH_4 emissions had increased dramatically in three countries, including Brazil (by 150%), Canada (by 53%) and India (by 24%), whilst it decreased by 2.2% in Australia. The main reason for the decline in Australia was the decline in emissions from enteric fermentation, attributed to reduced head of cattle and sheep and the use of a number of CH_4 reducing practices (Centre for International Economics, 2013).

On the other hand, in terms of LUCF activities, Australia was the only developed country in 1990 which was a net GHG emitter (43.1 Mt of CO_2e); the USA (−846.6 Mt of CO_2e) and Canada (−67.5 Mt of CO_2e) were both net sequesters of GHGs. In 2009, Australia remained a net GHG emitter; however, compared to 1990, its emissions from LUCF activities had increased by 25%. On the other hand, the USA and Canada remained net GHG removers in 2009 but, compared to 1990, Canada's net GHG amount removed through LUCF activities decreased by 82%. For developing countries, only single year data (1994) are available. These data show that

Table 4
Agricultural methane emissions (thousand metric tons of CO2 equivalent) and net GHG emissions/removals by LUCF (Mt of CO2 equivalent).

Year	Australia		Brazil		Canada		China		Argentina		India		United States	
	CH4 emissions	NET LUCF emissions	CH4 emissions	NET LUCF emissions	CH4 emissions	NET LUCF emissions	CH4 emissions	NET LUCF emissions	CH4 emissions	NET LUCF emissions	CH4 emissions	NET LUCF emissions	CH4 emissions	NET LUCF emissions
1970	71049.0		126426.7		18899.8		546059.3		70090.7		306374.4		183159.1	
1971	71299.4		123039.2		19006.9		578240.5		71391.9		308 106.5		187 591.1	
1972	78476.6		130687.1		19188.4		581221.8		74545.8		305907.0		188181.6	
1973	71135.5		131433.2		19375.1		575909.1		77497.4		310671.0		190110.4	
1974	75657.4		138377.0		19758.2		578656.5		77495.5		310730.1		196702.0	
1975	81516.1		144423.2		20180.5		576549.0		79163.0		316067.8		198670.5	
1976	86607.3		160831.4		20023.5		578669.8		81324.6		314999.2		193168.4	
1977	81711.9		160137.2		19571.7		562640.9		84699.4		321284.0		190331.7	
1978	72367.1		161237.2		18934.7		543622.9		80597.9		324434.5		188086.2	
1979	75951.2		164248.0		18759.5		533248.0		79536.5		324804.2		184795.8	
1980	77142.7		178343.6		19458.8		530830.0		78082.2		330157.5		190553.3	
1981	66259.1		179450.1		19582.5		518891.5		76166.3		334752.0		195438.9	
1982	72806.3		182728.5		19578.5		513074.9		74180.0		333773.2		193240.3	
1983	64423.4		182115.3		19108.0		513363.9		75447.8		344316.2		187570.1	
1984	65651.0		183090.1		18942.9		509024.0		76118.5		347300.2		188030.0	
1985	76341.8		184605.5		18625.0		495018.2		75307.6		349208.2		183038.9	
1986	71805.0		192176.6		18143.8		501386.9		74253.8		353305.6		177973.3	
1987	66154.2		201195.9		17903.6		504941.8		73259.0		348474.5		174414.1	
1988	67192.3		201865.8		18311.2		504630.3		75509.4		358638.6		175257.6	
1989	70496.7		206009.2		18690.5		516974.2		77006.2		362918.7		172495.7	
1990	75606.9	43.1	209548.2		18925.9	−67.5	523399.9		78230.6		366992.2		172736.8	−846.6
1991	77774.3	166.4	220055.9		18975.5	−41.2	516219.0		76797.4		368891.9		173900.8	−818.7
1992	73224.7	124.6	230681.2		19691.9	−89.6	508465.9		77315.2		370329.7		178039.5	−804.5
1993	69830.6	−22.9	238007.0		19805.0	−20.3	490048.6		75664.3		371699.6		179564.6	−758.6
1994	79460.8	−19.7	241140.2		20177.9	−23.7	491135.0	−407.5	75654.8		373675.2	14.3	183820.6	−850.1
1995	69627.5	104.7	253110.2		21375.9	186.0	507537.1		74557.1		374622.7		186398.6	−795.4
1996	71201.5	−1.7	244335.6		22467.8	−29.7	511414.0		72704.1		376621.7		186661.8	−679.8
1997	74225.0	−9.3	245648.0		22618.4	−71.7	490965.5		72126.2		375072.9		185342.9	−727.7
1998	72866.2	127.3	251275.4		22857.4	116.2	496318.7		70173.4		376705.3		185744.1	−602.0
1999	77246.2	10.5	247020.0		23057.4	7.8	497778.9		72228.4		379042.7		186877.6	−503.7
2000	78559.8	−13.5	245526.1		23318.2	−62.1	485764.7		71641.2	−43.3	376022.8		185222.2	−540.3
2001	82927.7	−42.5	258561.5		23997.1	−57.7	482191.0		71274.6		377200.5		185455.2	−635.8
2002	75267.6	333.0	271907.8		24367.8	87.4	480732.5		69524.2		370006.9		186293.1	−830.6
2003	67772.4	167.1	282633.4		24168.4	43.0	473684.3		72728.1		373800.6		185962.5	−980.2
2004	74592.3	−195.3	299045.9		25591.4	96.8	501160.8		72219.7		373435.2		187157.3	−1033.6
2005	70127.5	44.8	302675.4	1329.1	26137.6	53.5	516949.4		71860.3		375977.1		190585.6	−1027.9
2006	68703.2	48.2	302080.5		27234.6	64.6	538545.0		71811.1		376727.0		192380.0	−1014.5
2007	78770.2	342.5	308631.7		27969.2	51.4	557330.6		71903.2		378692.6		194811.3	−1013.4
2008	69460.8	69.5	315949.8		28900.2	−16.9	577909.3		71924.4		380029.1		196940.0	−1007.3
2009		54.0				−12.1								−990.1
Change%	−2.2	25.1	149.9		52.9	82.1	5.8		2.6		24.0		7.5	−17.0

China (−407.5 Mt of CO_2e) and Argentina (−43.3 Mt of CO_2e) were net removers, while Brazil (1329.1 Mt of CO_2e) and India (14.3 Mt of CO_2e) were net GHG emitters from LUCF activities. The worst outcomes, in Australia and Brazil, were due to high forest clearing rates mainly for cultivating crops and pastures and building infrastructure (Bradshaw, 2012; Sawaya and Nappo, 2009). For example, over the past 200 years, Australia has lost about 40% of its total forest cover (Bradshaw, 2012). On the other hand, better outcomes in China are due to its encouraging plantation policies and supporting economic tools (Turnbull, 2007).

5. Conclusions and recommendations

Using time series data from 1961 to 2012, this study analysed the trends and magnitudes of N_2O emissions from arable land due to the use of synthetic N fertilisers, farm manure and retention of crop residues in seven major agricultural production countries. In 1961, total emission from these three sources was greatest in the USA, followed by China, Brazil, India, Argentina, Canada and Australia. However, by 2012, China and India had both surpassed the USA, whilst Australia still had the lowest aggregate N_2O emissions of the seven countries. During the 52 year period, crop PIN increased in all countries with the highest increments observed in China, Brazil and Australia. However, when comparing 2012 crop PIN and total emissions from the three sources, Australia seems to perform better than others. Better farm efficiency in the Australian cropping sector has been achieved through structural changes; reduction in incentives and subsidies; investment in research and development; and adoption of new technologies and management practices. While there are lessons to be learned from the Australian experience, Australia continues to perform poorly when emissions due to LUCF activities are considered.

From 1961 to 2012, the proportional contribution of synthetic N fertilisers to total emissions from these three sources increased tremendously whilst manure related emissions decreased sharply. Similarly, in all countries, during the same period, the proportional contribution of crop residue also decreased. Such trends in these countries suggest that synthetic N fertilisers are now a preferred option to increase crop production. Therefore, finding ways of reducing synthetic N-fertilisers use without compromising productivity is the challenge of the century.

In the past, legume based cropping/rotational system were very popular for providing N nutrients to the plant. However, there is currently a debate within the scientific community as to whether legume-based N is equally harmful for global warming as the synthetic N fertiliser. Legume-based N is derived from solar energy whereas production of synthetic N fertiliser requires significant amounts of fossil fuel. Thus, legumes should be favoured. Synthetic N fertilisers have also been linked to numerous environmental problems including eutrophication, groundwater contamination and stratospheric ozone destruction (Crews and Peoples, 2004). Therefore, introducing legumes into the cropping/rotational system could provide a better solution to the environment.

Acknowledgement

This study was co-funded by “National Natural Sciences Foundation” of China (Grant No. 433 41371537 and 41401656) and the “Chinese Academy of Sciences Visiting Professorship for Senior International Scientist Program” (Grant No: 2012T1Z45). We would like to thank them for their financial and logistic support. We would also like to extend our profound gratitude to Dr Kathryn Reardon-Smith for her extensive editing work and Dr Uttam Shrestha for assisting in preparing Fig. 1. Finally, we cordially thank anonymous referees for their highly valuable suggestions, which were gratefully acknowledged.

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