Annual crop legumes may not mitigate greenhouse gas emissions because of the high carbon cost of nitrogen fixation

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Abstract
A large uncertainty in constructing grain cropping Life Cycle Assessments (LCAs) is the effect of a particular crop, or sequence of crops, on soil C stocks. We propose that the C cost of legume N_2 fixation, estimated to be ca. 20 kg CO_2/kg N fixed, will be expressed as reduced residue C returned to the soil and a possible net loss of soil C. Published pre-farm + on-farm greenhouse gas (GHG) emissions associated with N-fertilised wheat (60N) and canola (100N) and N_2-fixing field pea, grown in Australia's southern grains region, were combined with modelled effects of the same crops on soil C stocks. When effects of the crops on soil C were assumed to be neutral, canola had the highest emissions at 840 kg CO_2-e/ha with field pea the lowest (530 kg CO_2-e/ha). When estimated changes in soil C were included in the LCAs, canola's GHG emission were totally offset (-100 kg CO_2-e/ha), compared with a more than doubling of emissions for field pea to 1270 kg CO_2-e/ha. This is somewhat counter-intuitive to current thinking that the substitution of fertiliser N with legume fixed N is an effective strategy for GHG emissions mitigation and highlights the need for simple, accurate methodologies for determining net changes in soil C for individual crops.

Key Words
Greenhouse gas emissions, legume nitrogen fixation, carbon dioxide equivalents, respiratory cost

Introduction
The agricultural sector, like other sectors, has a responsibility to contribute to national greenhouse gas (GHG) emissions reduction targets which, in the case of grain production, are likely to be achieved through adoption by farmers of management practices that minimise nitrous oxide (N_2O) emissions from cropping soils and, at the same time, enhance capture of C from the atmosphere and its retention in the soil (e.g. Gan et al. 2014). Cradle to farm-gate life cycle assessments (LCA) of grain cropping indicate the production, transport and use of N fertilisers to be a major source of both CO_2 and N_2O emissions (Gan et al. 2014; Brock et al. 2016). Because of this, research has been directed at assessing possible mitigation strategies such as substituting fertiliser N inputs with legume fixed N and reducing denitrification losses of applied fertiliser N using protected, slow release fertiliser formulations (Nemecek et al. 2008; Misselbrook et al. 2014; Lam et al. 2016).

The net changes in soil C during growth of a particular crop or sequence of crops can represent a major source or sink of GHG emissions. Crop management practices such as cropping intensification, residue retention and optimised agronomy and nutrient management, including use of organic fertilisers, increase net primary productivity (NPP) and net soil C balances. On the other hand, practices such as fallowing and residue removal decrease them (Paustian et al. 2000; Christopher and Lal 2007). Pasture and forage legumes, grown in sequence with annual grain crops or managed as components of multi-species pastures and grasslands, have been shown to contribute to soil C stocks (e.g. Lam et al. 2013). However, the annual pulse and oilseed legumes, grown primarily as sole crops on close to 220 Mha globally, are not reported as having similarly consistent benefits for soil C (Christopher and Lal 2007; Jensen et al. 2012; Shrestha et al. 2013).

The C cost of N_2 fixation by nodulated legumes is significant, resulting in less retention of photosynthate and loss of net primary productivity (NPP). Herridge et al. (2016) reported that legumes may respire 20–25% of net photosynthate as nodular respiration, assuming Ndfa values of 67–83%. The data indicated average reductions 13.7 kg DM/kg N fixed, equivalent to 20 kg CO_2/kg N fixed. The authors concluded that ca. 45% of the difference in NPP of the annual crop legumes and N-fertilised wheat in Australia could be directly related to the C cost of N_2 fixation. These numbers are not relevant to current GHG accounting. What is relevant is the impact of N_2 fixation and reduced NPP on production of residues and potentially on soil C.

In this paper, we assess the impact on pre-farm plus on-farm GHG emissions of including estimated changes in soil C stocks associated with single crops of N-fertilised wheat and canola and N_2-fixing field pea. The GHG emissions inventories for the three crops, determined using life cycle assessment (LCA) methodology, were as reported in Brock et al. (2016).

Methods

Region of study, crops and LCAs

The study was focussed on Wagga Wagga (147º35' E, 35º05' S) in the southern grains region of Australia. The C:N ratio of the soil in which the crops were grown was assumed to be 11:1; thus, 880 kg C/ha was respired during each 12-month period associated with the assumed mineralisation of 80 kg soil organic N/ha. Crops for which LCAs were constructed were wheat +60 kg/ha fertiliser N, canola +100 kg/ha fertiliser N and field pea 0N. Grain yields and proteins (3.0 t/ha @ 10.5% grain protein (GP) for wheat, 2.0 t/ha @ 18% GP for canola and 1.8 t/ha @ 23% GP for field pea), N_2 fixation by field pea (estimated at 100 kg N/ha) and inputs, including fertiliser N, for the 6 crops were based on the published gross margin budgets for the NSW southern zone (east) (NSW Department of Primary Industries 2012), the NSW Grains Report Summary 1993–2013 (Scott 2013) and from many published and unpublished reports of grain cropping in the region.

Cradle-to-farm gate LCAs were conducted using SimaPro software as described in Brock et al (2016). An EF of 0.2% for emissions of N_2O from fertiliser, soil and residue N sources was used (Australian Government 2015). Changes in soil C stocks were not included in the published LCAs. Rather, it was assumed that there were no changes in soil C associated with the cropping (Brock et al. 2016).

Table 1. Life cycle inventories of cradle to farm-gate GHG emissions (kg CO_2-e/ha) for wheat, canola and field pea in the grains region of south-eastern Australia (source: Brock et al. 2016)

	Wheat 60N	Canola 100N	Field pea 0N
		CO_2–e/ha	
Production of lime (95% purity)	20	20	20
CO_2 emissions from lime application on-farm	105	105	105
Production and application of herbicides and pesticides	60	52	72
Production and transport of diesel	14	13	11
Embodied energy in on-farm equipment	10	11	11
Seed	18	2	33
Crop residue burning	11	1	0
Diesel used on-farm for sowing, harvesting	38	40	31
Background soil N_2O emissions	75	75	75
Production and transport of fertilisers	167	266	91
Emissions of N_2O and CO_2 from applied fertilisers + emissions from fertiliser spreading	157	256	10
Pea residue N	0	0	70
Total	676	840	530

Estimating changes in soil C associated with wheat, canola and field pea

A simple empirically-based set of linked algorithms was used to estimate production of residue biomass and C from the wheat, canola and field pea at the described yield and grain protein levels. Key factors and assumptions in the algorithms were: HI values of 0.40 for wheat, 0.28 for canola and 0.37 for field pea; multiplication factor of 1.4 to calculate total crop biomass from shoot biomass; multiplication factor of 0.4 to calculate plant C from plant biomass; multiplication factors of 0.3 (wheat) and 0.35 (canola and field pea) to calculated net C retained in soil OM from residue C (Ladd 1987); 5% of applied fertiliser N immobilised in soil; C:N ratio of soil OM of 11:1 (Herridge 2013).

Results

Area-based GHG emissions for production of the individual crops ranged from 530 kg CO_2-e/ha (field pea) to 841 kg CO_2-e/ha (canola) (Table 1). The greatest source of emissions was the production, transport and use of N fertiliser with an almost 50:50 balance of pre-farm emissions (production and transport of the fertilisers) and on-farm (fertiliser spreading and from the soil as CO_2 and N_2O). Fertiliser-associated emissions represented 19% of total emissions for field pea, compared with 48% and 62% for wheat and canola, respectively. For field pea, 13% of emissions were associated with mineralisation of residues.

Net changes in soil C associated with the wheat, canola and field pea crops were estimated to vary between a loss of 200 kg C/ha (740 kg CO_2-e/ha) for field pea to a gain of 260 kg C/ha (940 kg CO_2-e/ha) for canola (Table 2). Wheat had an almost neutral effect of soil C. It is worth noting that the relativities of the calculated biomass values for wheat (100), canola (96) and field pea (65) in Table 2 were very similar to published values for wheat (100), canola (102) and field pea (70) in the Unkovich et al. (2010) review of harvest indices of Australian grain crops.

For each crop, estimated changes in soil C were subtracted from the total pre-crop + in-crop GHG emissions to determine the C footprints on an area basis (column 4, Table 3) and per tonne grain (final column, Table 3). Canola was the largest emitter when effects of the cropping on soil C stocks were assumed to be neutral. When estimated changes in soil C were included in the LCAs, canola had a negative C footprint, i.e. there was net C sequestration. Conversely, field pea went from being the smallest emitter to the largest when the calculated changes in soil C were included.

Table 2. Sequence of calculations to determine the amounts of C returned to the soil following grain harvest and the 12-month net C balances for wheat, canola and field pea in the grains region of south-eastern Australia (see Herridge (2013) for additional details)

	Wheat 60N	Canola 100N	Field pea 0N
Grain yield (t/ha @ 12% moisture)	3.0	2.0	1.8
Shoot biomass (t/ha)	7.41	7.14	4.85
Total crop biomass including below-ground (t/ha)	10.38	10.00	6.79
Residue biomass (t/ha)	7.19	7.72	4.84
Net C retained in Soil OM (%)	30	35	35
Net C retained in Soil OM (kg/ha)	863	1081	678
C immobilised into Soil OM with fertiliser N	33	55	0
Total C returned (kg C/ha)	896	1136	678
C released to atmosphere with mineralisation of 80 kg /ha SOM-N (kg C/ha) (assume C:N ratio of 11:1)	880	880	880
Net C balance (kg C/ha)	16	256	-202
Net C balance (kg CO_2 –e/ha)	60	940	-740

Conclusion

There are uncertainties in constructing grain cropping LCAs and quantifying the C footprints of individual crops or crop sequences. When effects of N-fertilised wheat and canola and N_2–fixing field pea at Wagga Wagga in south-eastern Australia on soil C were assumed to be neutral, pre-farm plus on-farm GHG emissions were lowest for the field pea and highest for N-fertilised canola. This was reversed when modelled effects of the crops on soil C were included in the GHG inventories. Field pea was estimated to produce less biomass and residue C than the other two crops, likely to be related to the significant C cost to the crop of N_2 fixation, which resulted in a net loss of soil C. Canola, on the other hand, had a large positive effect on soil C because of the its relatively low HI.

Table 3. Carbon footprints for wheat, canola and field pea, including estimated net changes in soil C in the grains region of south-eastern Australia

Crops and sequences	GHG emissions (kg CO_2 –e/ha)	Changes in soil C (kg CO_2 –e/ha)	C footprint (kg CO_2 –e/ha)[1]	GHG emissions (kg CO_2 –e/t grain)	Changes in soil C (kg CO_2 –e/t grain)	C footprint (kg CO_2 –e/t grain)[2]
Individual crops						
Wheat 60N	676	+60	617	225	+20	205
Canola 100N	840	+940	-100	420	+470	-50
Field pea 0N	530	-740	1270	294	-412	706

The net loss of soil C under field pea more than doubled its C footprint. On the other hand, GHG emissions associated with N-fertilised canola were completely offset by net sequestration of residue C in the soil. These results are somewhat counter-intuitive to current thinking that the substitution of fertiliser N with legume fixed N is an effective strategy for GHG emissions mitigation. Clearly, the outputs from our modelling need to be validated by field-based experimentation and additional modelling. We concur with other reports that simple, accurate methodologies for determining net changes in soil C for individual crops and short-term crop sequences are urgently required (e.g. Olander and Haugen-Kozyra 2011).

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