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

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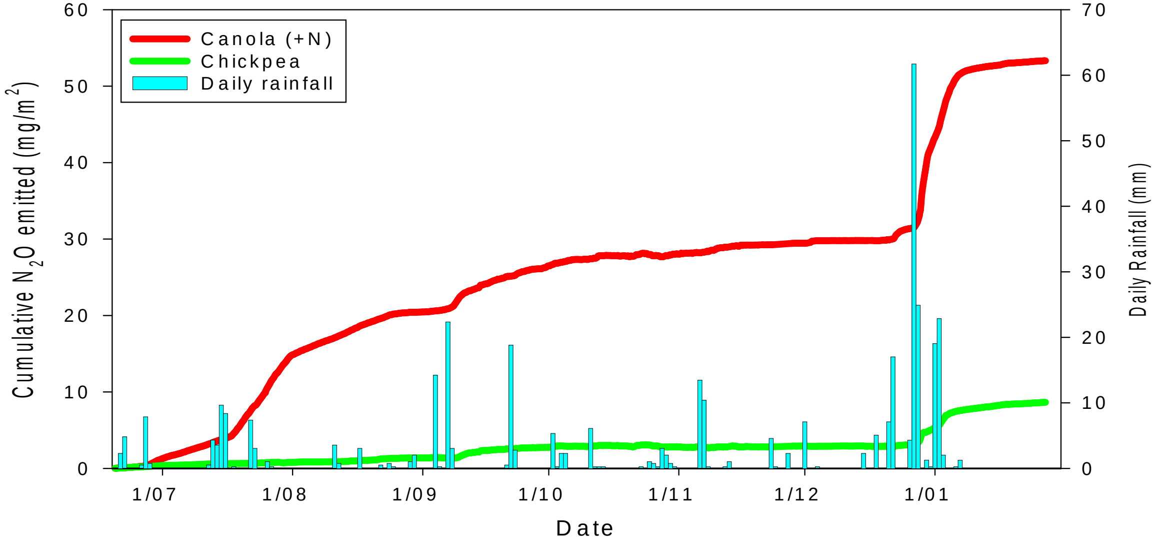
Greenhouse gas emissions of legume fixed N vs fertiliser N

- N_2–fixing legumes produce less greenhouse gas (CO_2 and N_2O) emissions than N-fertilised crops because of:
  - Emissions of CO_2 from production and transport of fertiliser N and from dissolution of urea in the soil
  - Greater emissions of N_2O from soil associated with fertiliser N use than from N_2 fixing legumes
  - In GHG emissions accounting there are no emissions (CO_2 or N_2O) directly attributed to N_2 fixation (IPCC 2006)
- Increased use of N_2-fixing legumes represents potentially-effective strategy for GHG mitigation*

*Robertson GP et al. (2000) Science 289:1922-25; Gregorich EG et al. (2005) Soil & Tillage Research 83:53-72; Mosier AR et al. Nutr Cycl. Agroecosyst. 72:67-76; Lemke RL et al. (2007) Agronomy Journal 99:1719-25; Lupwayi NZ and Kennedy AC (2007) Agronomy Journal 99:1700-09; Smith P et al. (2008) Phil. Trans. Royal Soc. B 363:789-913; Smith P et al. (2013) Global Change Biology 19:2285-2302

Seasonal profiles of N_2O emissions – fertiliser N and legume fixed N

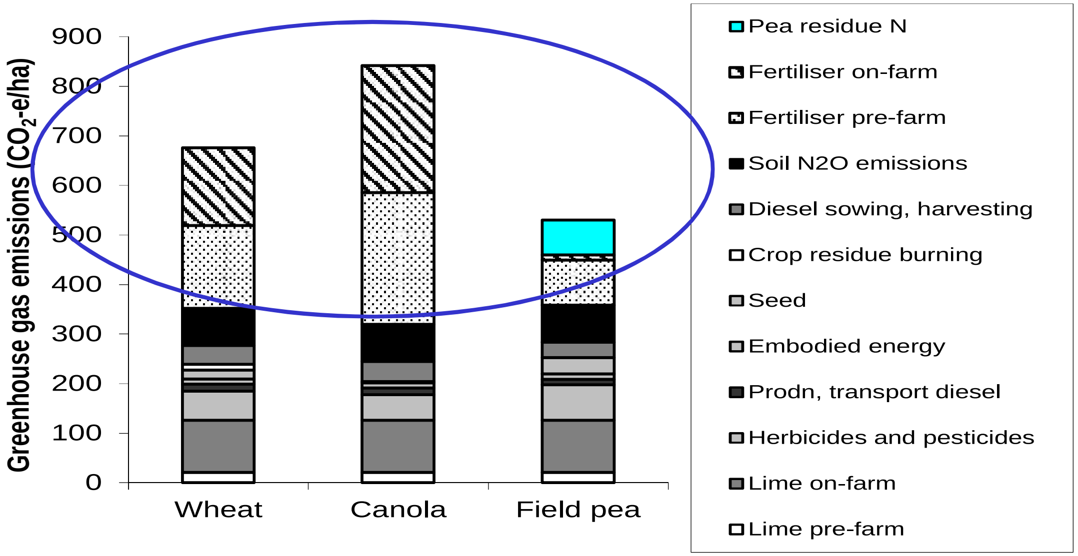
- Data from N_2O emission monitoring in northern NSW
- Clearly, less emissions from the N_2 fixing chickpea than from the N-fertilised canola
- Data typical of many data sets from Australia and elsewhere (used to test mitigation strategies and calculate EFs)
- Supports the notion that substitution of fertiliser N inputs by legume fixed N results in reduced N_2O emission…



Schwenke et al. (2015) Agric Ecosyst & Environ 202, 232-242

Greenhouse gas emissions for wheat, canola and field pea – southern NSW

- Total GHG emissions determined for wheat (3.0 t/ha), canola (2 t/ha) and field pea (1.8 t/ha) using Life Cycle Assessment (LCA)
- Emissions of N_2O est. using EF of 0.2% (Aust Govt 2015)
- Emissions highest for N-fertilised canola (840) and lowest for N_2-fixing field pea (530)
- Differences related to fertiliser N inputs
  - Canola 100N
  - Wheat 60N
  - Field pea 0N (100N fixed)
- **But, soil C changes not included**



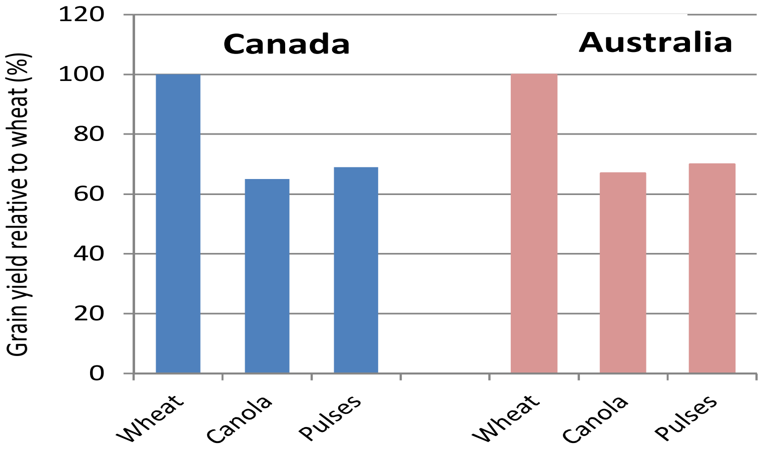
Source: Brock PM et al. (2016) Crop & Pasture Science 67:812–822. Cradle-to-farmgate LCA constructed using SimaPro (2011) software and both Australasian LCA Database and the Swiss Ecoinvent Database

Soil C changes and crop residues

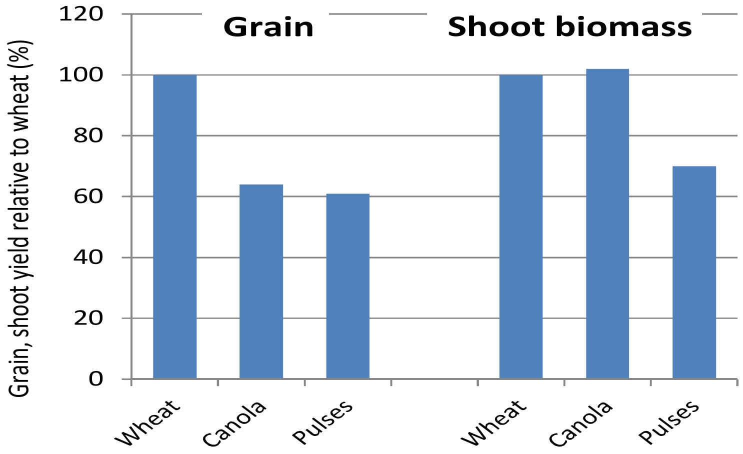
- **But, soil C changes not included…**
- Can represent a major source or sink of CO_2 emissions
- Soil C changes, in the absence of erosion losses, largely determined by difference between residue C inputs and soil respiration
- In many grain cropping LCAs, assumption is that soil C stocks do not change
- N_2-fixing legumes don't grow as well as mineral N-dependent cereal and oilseed crops….

Legume, cereal and canola yields

- Statistical and empirical data tell us that average **grain yields** of legumes ca. 30% less than those of cereals
- Not because of lower harvest index (HI); average HIs from database (Unkovich et al. 2010) were 0.37 (wheat) and 0.37 (legumes) but 0.28 (canola)
- Average **biomass yields** of legumes also 30% less than those of cereals
- Why is that?



Source: FAOSTAT (2016)



Source: Unkovich et al. (2010) involving ca. 23,000 grain values and ca. 1,700 shoot biomass values

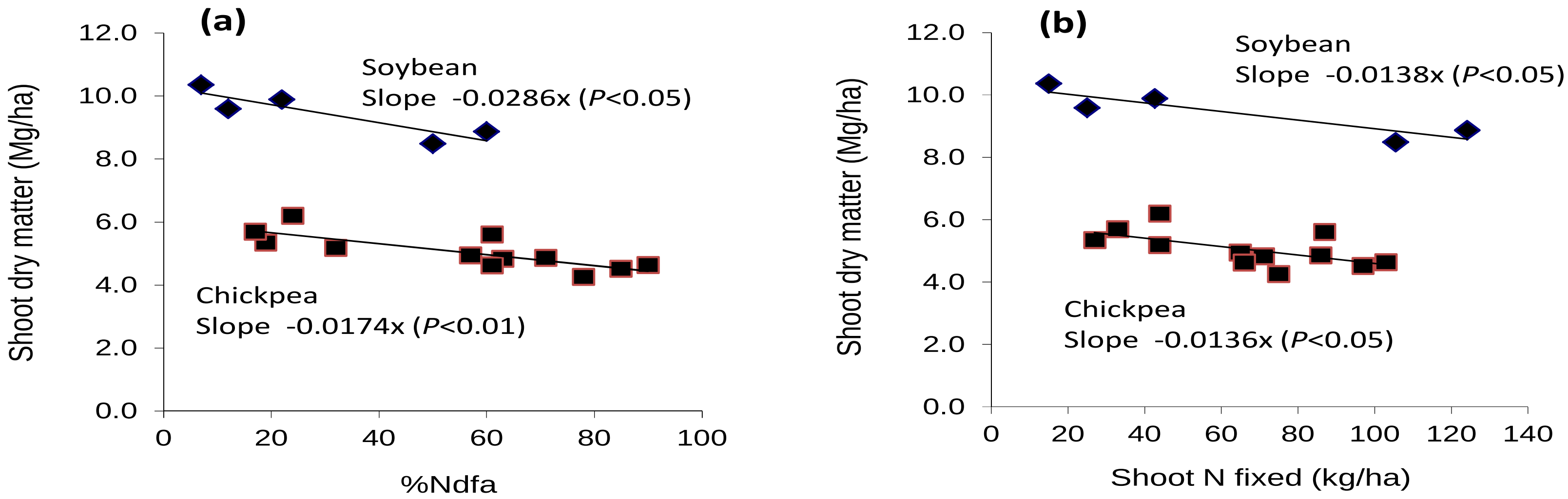
Legume fixed N is not free….

- There is a C cost of N_2 fixation by nodulated legumes related to the process of N_2 fixation, plant and bacterial cell maintenance etc., a respiratory cost
- Values in table from glasshouse-cultured plants and theoretical calculations vary 6-17 kg CO_2/kg N fixed.
- Minchin and Witty (Plant Respiration, Springer, 2005) summarised current knowledge, reporting 18-37 kg CO_2/kg N with average of 24 kg CO_2/kg N fixed
- Jensen ES (1986) data showed fully N_2 fixing pea had 37% less DM than fully N-dependent plants and there was a loss 19.8 g DM/g N fixed, equivalent to 29 g CO_2/g N fixed

Crop	C resp/N fixed	CO_2 resp/N fixed (g/g)	Reference
Cowpea	1.5	5.7	Layzell DB et al. (1979) Plant Physiol. 64:888-91
White lupin	3.6	13.4	
Cowpea and white lupin	4.6	16.8	Layzell DB et al. (1988) Planta 173:117-27
Nodulated soybean	5.2	19.0	Finke RL et al. (1982) Plant Physiol. 70:1178-84
Nitrate-fed soybean	2.7	9.7	
Diff	2.5	9.3	

Legume fixed N is not free….

- What about data for field-grown legumes?
- Data sets from Doughton JA et al. (1993) AJAR 44:1403-13 involving chickpea and Herridge DF et al. (1990) Plant Physiol. 93:708-16 involving irrigated soybean (each value mean of 7 cvs) indicate:
  - Fully N_2 fixing chickpea, soybean had ca. 30% less DM, C than fully N-dependent plants
  - 13.6 kg DM reduced/kg N fixed = 5.44 kg C or 19.9 kg CO_2/kg N fixed (chickpea)
  - 13.8 kg DM reduced/kg N fixed = 5.52 kg C or 20.2 kg CO_2/kg N fixed (soybean)



Soil C changes and crop residues

- **But, soil C changes not included…**
- Soil C changes, in the absence of erosion losses, largely determined by difference between residue C inputs and soil respiration
- Can represent a major source or sink of CO_2 emissions
- In many grain cropping LCAs, assumption is that soil C stocks do not change
- N_2-fixing legumes don't grow as well as mineral N-dependent cereal and oilseed crops (**now know why**)
- **Reduction in biomass means less residue C returned to the soil from legumes after grain harvest**

Soil C changes....

- Back to the LCA and impacts of the different crops on soil C
- Values in table modelled using Nbudget (Herridge 2013*); difficult even impossible to measure for single crops (50 t C/ha backgrounds). Assumed:
  - annual mineralisation from SOM of 80 kg N/ha (880 kg C/ha)
  - 5% fertiliser N immobilised
  - 30-35% residue C incorporated into SOM (Ladd JN (1987)[1]
  - HIs of 0.40 for wheat, 0.28 for canola, 0.37 for field pea
  - AG+BG biomass = AG biomass*1.4

Crop or sequence	Grain yield (t/ha)	Above-ground biomass (t/ha)	AG+BG residue biomass (t/ha)	AG+BG residue C (t/ha)	C retained in soil (t/ha)[1]	Net change in soil C (t/ha)
Wheat	3.0	7.4	7.2	2.88	0.86	+0.02
Canola	2.0	7.1	7.7	3.09	1.08	+0.26
Field pea	1.8	4.9	4.8	1.94	0.68	-0.20

*Herridge DF (2013). Managing legume and fertiliser N for northern grains cropping. GRDC, Canberra. 87 pp. (see poster this Conference session 4A)

Soil C changes….

	Wheat-wheat 120N	Canola-wheat 160N	Field pea –wheat 140N
C balance	+40	+310	-100
N balance	-8	+20	+7

- Including estimated changes in soil C in GHG (C footprint) LCAs reverses the order with canola and canola-wheat sequence having the lowest C footprint and field pea and field pea-wheat sequence the highest

Crops and sequences	Total GHG emissions (kg CO_2 –e/ha)	Changes in soil C (kg CO_2 –e/ha)	C footprint (kg CO_2 –e/ha)
Individual crops			
Wheat 60N	676	+60	617
Canola 100N	840	+940	-100
Field pea 0N (100N fixed)	530	-740	1270
2-year sequences			
Wheat 60N–wheat 60N	1350	+146	1204
Canola 100N–wheat 60N	1517	+1136	380
Field pea (100N)–wheat 40N	1114	-366	1480

Conclusions

- Uncertainties in constructing LCIs and quantifying C footprints of crops and sequences
- Agricultural grain legumes fix 40-50 million tonnes N annually, rate highly for environmental impact categories, e.g. fossil fuel energy demand, eutrophication potential, but not necessarily for global warming potential (GHG emissions)
- There is a direct C cost of N_2 fixation for the legume that results in ca. 13.8 kg DM loss/kg N fixed (20 kg CO_2/kg N fixed). This direct cost is not factored into GHG emissions accounting
- Simple modelling suggests the loss of legume DM translates into reduced residue C returned to the soil and reduced incorporation of C into soil OM
- In reducing the C (and other) footprint of grain cropping, need to be strategic with crop sequences optimising N inputs from legume N_2 fixation (high yields, low min-N soils) and C inputs from canola and cereals (high yields)
- Definitely needs more analysis