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

David Herridge\textsuperscript{1} and Pip Brock\textsuperscript{2}
\textsuperscript{1}University of New England
\textsuperscript{2}NSW Dept Primary Industries
Greenhouse gas emissions of legume fixed N vs fertiliser N

- $\text{N}_2$-fixing legumes produce less greenhouse gas ($\text{CO}_2$ and $\text{N}_2\text{O}$) emissions than N-fertilised crops because of:
  - Emissions of $\text{CO}_2$ from production and transport of fertiliser N and from dissolution of urea in the soil
  - Greater emissions of $\text{N}_2\text{O}$ from soil associated with fertiliser N use than from $\text{N}_2$ fixing legumes
  - In GHG emissions accounting there are no emissions ($\text{CO}_2$ or $\text{N}_2\text{O}$) directly attributed to $\text{N}_2$ fixation (IPCC 2006)

- Increased use of $\text{N}_2$-fixing legumes represents potentially-effective strategy for GHG mitigation

Seasonal profiles of $\text{N}_2\text{O}$ emissions – fertiliser $\text{N}$ and legume fixed $\text{N}$

- Data from $\text{N}_2\text{O}$ emission monitoring in northern NSW
- Clearly, less emissions from the $\text{N}_2$ 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 $\text{N}$ inputs by legume fixed $\text{N}$ results in reduced $\text{N}_2\text{O}$ emission...

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 N₂O est. using EF of 0.2% (Aust Govt 2015)
- Emissions highest for N-fertilised canola (840) and lowest for N₂-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

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 \textbf{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 \textbf{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 N₂ fixation by nodulated legumes related to the process of N₂ fixation, plant and bacterial cell maintenance etc., a respiratory cost.
- Values in table from glasshouse-cultured plants and theoretical calculations vary 6-17 kg CO₂/kg N fixed.
- Minchin and Witty (Plant Respiration, Springer, 2005) summarised current knowledge, reporting 18-37 kg CO₂/kg N with average of 24 kg CO₂/kg N fixed.
- Jensen ES (1986) data showed fully N₂ 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 CO₂/g N fixed.

<table>
<thead>
<tr>
<th>Crop</th>
<th>C resp/N fixed</th>
<th>CO₂ resp/N fixed (g/g)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cowpea</td>
<td>1.5</td>
<td>5.7</td>
<td>Layzell DB et al. (1979) Plant Physiol. 64:888-91</td>
</tr>
<tr>
<td>White lupin</td>
<td>3.6</td>
<td>13.4</td>
<td></td>
</tr>
<tr>
<td>Nodulated soybean</td>
<td>5.2</td>
<td>19.0</td>
<td>Finke RL et al. (1982) Plant Physiol. 70:1178-84</td>
</tr>
<tr>
<td>Nitrate-fed soybean</td>
<td>2.7</td>
<td>9.7</td>
<td></td>
</tr>
<tr>
<td>Diff</td>
<td>2.5</td>
<td>9.3</td>
<td></td>
</tr>
</tbody>
</table>
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\textsubscript{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\textsubscript{2}/kg N fixed (chickpea)
  - 13.8 kg DM reduced/kg N fixed = 5.52 kg C or 20.2 kg CO\textsubscript{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

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

*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....

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.

<table>
<thead>
<tr>
<th>Crops and sequences</th>
<th>Total GHG emissions (kg CO₂-e/ha)</th>
<th>Changes in soil C (kg CO₂-e/ha)</th>
<th>C footprint (kg CO₂-e/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Individual crops</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheat 60N</td>
<td>676</td>
<td>+60</td>
<td>617</td>
</tr>
<tr>
<td>Canola 100N</td>
<td>840</td>
<td>+940</td>
<td>-100</td>
</tr>
<tr>
<td>Field pea 0N (100N fixed)</td>
<td>530</td>
<td>-740</td>
<td>1270</td>
</tr>
<tr>
<td><strong>2-year sequences</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheat 60N–wheat 60N</td>
<td>1350</td>
<td>+146</td>
<td>1204</td>
</tr>
<tr>
<td>Canola 100N–wheat 60N</td>
<td>1517</td>
<td>+1136</td>
<td>380</td>
</tr>
<tr>
<td>Field pea (100N)–wheat 40N</td>
<td>1114</td>
<td>-366</td>
<td>1480</td>
</tr>
</tbody>
</table>
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\textsubscript{2} fixation for the legume that results in ca. 13.8 kg DM loss/kg N fixed (20 kg CO\textsubscript{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\textsubscript{2} fixation (high yields, low min-N soils) and C inputs from canola and cereals (high yields)
- Definitely needs more analysis