Rotational benefits of legume $N_2$ fixation – universal or with caveats?

David Herridge, UNE
This talk.....

1. Legumes in agriculture
2. The value of legume N$_2$ fixing: low vs high input systems
   1. Pigeonpea-maize intercropping in southern Africa
   2. Chickpea in Australia
3. Environmental credentials of N$_2$ fixing legumes vs mineral-N dependent crops
   1. Nitrous oxide (N$_2$O) emissions
   2. C footprints
Legumes in agriculture

- Legumes have been cultivated and eaten for more than 5000 years.
- Lucerne was cultivated in Babylonia (Iraq) nearly 3,000 years ago.
- About 2500 years ago, Theophrastus wrote “Beans...are not burdensome to the ground; they even seem to manure it...”
- Varro wrote in 37 B.C. “Legumes should be planted on light soils, not so much for their own crops as for the good they do to subsequent crops”
- In Australia..
Legumes in agriculture...

JL Thompson summarised the reasons for using legumes in farming systems in NSW (Australia):

- More economical of manure
- More economical of nutrients in the soil
- Benefits of deep-rooted and air feeding crops for following crops
- Benefits for following cereals from leguminous crops
- Allows for better distribution of labour on the farm
- Allows for better weed control
- Management of plant pathogens and insects
- Allows for better management of livestock
- Spread of economic risk
Legumes in agriculture...

JL Thompson summarised the reasons for using legumes in farming systems in NSW (Australia):

- More economical of manure
- More economical of nutrients in the soil
- Benefits of deep-rooted and air feeding crops for following crops
- Benefits for following cereals from leguminous crops
- Allows for better distribution of labour on the farm
- Allows for better weed control
- Management of plant pathogens and insects
- Allows for better management of livestock
- Spread of economic risk

Thompson, JL (1895). Agricultural Gazette of NSW
N₂-fixing legumes in Australian agriculture

- 25,000 grain farmers plant ca. 27 Mha crops annually
- Of that 2 Mha (8%) are legumes
- About 24 Mha legume-based pastures

- N fixed by crop legumes 150-200,000 t annually
- N fixed by pasture legumes ca. 2.5 Mt annually

Image: revised from Dalal and Chan (2001)
Australia’s reliance on legume N\textsubscript{2} fixation dwarfed by the situation in South America

Current production of soybean in Brazil and Argentina, Paraguay, Uruguay and Bolivia >160 Mt annually from >55 Mha

An estimated 80-90% of soybean currently inoculated with bradyrhizobia (ca. 50 Mha) and >3 Mha coinoculated with Azospirillum

N\textsubscript{2} fixation inputs of ca. 13 Mt N annually, valued at USD15 billion.
The intrinsic value of legume N$_2$ fixation changes with level of plant-available N supply

- In low N supply systems (low inputs, degraded soils), legume N$_2$ fixation can mean the difference between life- and livelihood-sustaining yields and food insecurity.
- In these systems, N$_2$-fixing legumes produce greater yields of grain and grain protein than mineral N-dependent crops and leave the soil with more plant-available N for the subsequent crop.
- With increasing N supply, the grain yield advantage disappears and planting of legume or non-legume becomes a purely economic and flexible decision.
Lowveld Research Unit, DARDLEA, Nelspruit, Mpumalanga Province, SA
Intercropping legumes (pigeonpea) and maize

- Fertiliser N a difficult option for low input small holder farmers
- Here, the N-fixing legume, pigeonpea, delivered N into the N-deficient system
- Intercrop system had almost twice the yield and protein productivity*
- The two crops complementary in sharing land area. Two-thirds PP growth after maize harvest

*All zero fertiliser N

Intercropping legumes (pigeonpea) and maize

- Grain yields of maize following maize-pigeonpea intercrop and sole pigeonpea similar and greater than following maize*
- 2-year revenue increased by 90% with intercrop and ca. 40% with sole pigeonpea, compared with maize-maize*
- Value for food security and economic livelihood with the intercrop system based on the N$_2$ fixing pigeonpea and the staple food maize

*All zero fertiliser N
By way of contrast, N$_2$-fixing chickpea in Australia

- In Australia, the value of legume N$_2$ fixation is more about economics than food security and livelihoods
- Published summary of data for rain-fed chickpea – wheat rotations, about 60 sites x years data*
- Average soil nitrate benefit 35 kg N/ha (= 50 kg fertiliser-N/ha)
- Average yield (cereal) benefit 0.7 t/ha, but as much as 1.5 t/ha when water not limiting
- Increased grain proteins of 1.0-1.5%
- Reductions in crown rot of wheat

**N₂-fixing chickpea in Australia**

- Mean values for 2 tillage treatments x 2 sites in long-term trials in northern NSW (Herridge et al. 1995).
- N inputs of 140 kg/ha from N₂ fixation (CP) and 100 kg/ha from fertiliser N (wheat)

<table>
<thead>
<tr>
<th></th>
<th>Chickpea-wheat 0N</th>
<th>Wheat 100N-wheat 0N</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Year 1 (chickpea or wheat 100N)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sowing soil nitrate</td>
<td>67</td>
<td>67</td>
</tr>
<tr>
<td>Grain yield (t/ha)</td>
<td>2.3</td>
<td>3.2</td>
</tr>
<tr>
<td><strong>Fertiliser N applied (kg/ha)</strong></td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td><strong>Total crop N fixed (kg/ha)</strong></td>
<td>140</td>
<td>0</td>
</tr>
<tr>
<td>Residue N (kg/ha)</td>
<td>133</td>
<td>55</td>
</tr>
<tr>
<td><strong>Year 2 (wheat 0N only)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sowing soil nitrate</td>
<td>102</td>
<td>74</td>
</tr>
<tr>
<td>Grain yield (t/ha)</td>
<td>2.8</td>
<td>1.8</td>
</tr>
</tbody>
</table>
**N₂-fixing chickpea in Australia**

- Gross margins for the chickpea-wheat rotation ca. 4 times that of the wheat-wheat rotation
- Economic benefit of chickpea essentially due to the extremely high grain price and not really driven by N benefits

<table>
<thead>
<tr>
<th>Year 1 (chickpea or wheat 100N)</th>
<th>Chickpea-wheat 0N</th>
<th>Wheat 100N-wheat 0N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain ($)¹</td>
<td>1,725</td>
<td>830</td>
</tr>
<tr>
<td>Cost of production ($)²</td>
<td>450</td>
<td>420</td>
</tr>
<tr>
<td><strong>Gross margin ($)</strong></td>
<td><strong>1,275</strong></td>
<td><strong>410</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year 2 (wheat 0N only)</th>
<th>Chickpea-wheat 0N</th>
<th>Wheat 100N-wheat 0N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain ($)¹</td>
<td>730</td>
<td>470</td>
</tr>
<tr>
<td>Cost of production ($)²</td>
<td>290</td>
<td>290</td>
</tr>
<tr>
<td><strong>Gross margin ($)</strong></td>
<td><strong>440</strong></td>
<td><strong>180</strong></td>
</tr>
</tbody>
</table>

¹Chickpea @ $750/t; wheat @$260/t; ²NSW DPI figures (2016)
But with increasing cost of fertiliser N...

- Rather than chickpea plantings being driven by the value of the grain, there was a time during 2007-09 when farmers looked to chickpea because of N\textsubscript{2} fixation.
- During 2007-09, the cost of fertiliser N doubled to close to $2/kg N – at that time chickpea grain prices were ca. $450/t.

![Urea price chart](Source: ABARES Australian commodity statistics 2014)
N$_2$–fixing legumes in agriculture...

- N$_2$–fixing legumes have substantial benefits in low input, small-holder systems, tied to food security and livelihoods.
- Farmers have more options in moderate-high input systems. They don’t need to rely on biologically fixed N, they can purchase and use industrially-fixed N.
- N$_2$ fixation can be a cost benefit of the particular crop, e.g. chickpea in Australia where the major driver of expanding production has been the grain price and other rotational effects.
- The reduced cost of production can sometimes be the major factor for planting legumes e.g. doubling of fertiliser N costs in 2007-09 and chickpea, fababean in Australia.
- But, legumes don’t grow or yield as well as mineral-N dependent cereal and oilseed crops.
- Why is that?
But, legumes don’t grow or yield as well as mineral-N dependent cereal and oilseed crops

- Average **grain yields** of legumes ca. 30% less than those of cereals
- Not necessarily 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 partly (ca. 45%) explained by the loss of plant biomass with N$_2$ fixation
- Reduction in biomass means less residue C returned to the soil after grain harvest

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.
- Values in table from glasshouse-cultured plants and theoretical calculations vary 6-17 kg CO\(_2\)/kg N fixed.

<table>
<thead>
<tr>
<th>Crop</th>
<th>C resp/N fixed</th>
<th>CO(_2) 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....

- Data sets from Doughton JA et al. (1993) AJAR 44:1403-13 involving field-grown chickpea and Herridge DF et al. (1990) Plant Physiol. 93:708-16 involving irrigated soybean (each value mean of 7 cvs) indicate:
  - N-fixing chickpea, soybean had ca. 30% less DM, C than min N-fed plants
  - 13.6 kg DM reduced/kg N fixed = 5.44 kg C or 19.9 kg CO₂/kg N fixed (chickpea)
  - 13.8 kg DM reduced/kg N fixed = 5.52 kg C or 20.2 kg CO₂/kg N fixed (soybean)

![Graphs showing relationship between Shoot dry matter (Mg/ha) and %Ndfa for Soybean and Chickpea](attachment:graphs.png)

![Graphs showing relationship between Shoot dry matter (Mg/ha) and Shoot N fixed (kg/ha) for Soybean and Chickpea](attachment:graphs2.png)
Legumes don’t grow or yield as well as mineral-N dependent cereal and oilseed crops

- Average grain yields of legumes ca. 30% less than those of cereals
- Not necessarily because of lower harvest index (HI); average HIs from database were 0.37 (wheat) and 0.37 (legumes) but 0.28 (canola)
- Average biomass yields of legumes also 30% less than those of cereals partly (ca. 45%) explained by the loss of plant biomass with N₂ fixation
- Reduction in biomass means less residue C returned to the soil after grain harvest

Source: FAOSTAT (2016)
Source: Unkovich et al. (2010) involving ca. 23,000 grain values and ca. 1,700 shoot biomass values
**Legumes in agriculture...**

JL Thompson summarised the reasons for using legumes in farming systems in NSW (Australia):

- More economical of manure
- More economical of nutrients in the soil
- Benefits of deep-rooted and air feeding crops for following crops
- Benefits for following cereals from leguminous crops
- Allows for better distribution of labour on the farm
- Allows for better weed control
- Management of plant pathogens and insects
- Allows for better management of livestock
- Spread of economic risk
- **Reduces greenhouse gas emissions**

Thompson, JL (1895). *Agricultural Gazette of NSW*, amended by Herridge, DF in 2011
N$_2$-fixing grain legumes have smaller C footprints than N-fertilised crops....

- General consensus* that N$_2$–fixing legumes produce less greenhouse gas (CO$_2$ and N$_2$O) 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$_2$O 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$_2$O) directly attributed to N$_2$ fixation (IPCC 2006)

- Increased use of N$_2$-fixing legumes represents potentially-effective strategy for GHG mitigation, although not such clear messages about impacts on soil C sequestration or loss

Automated chambers monitoring chickpea and canola
Inside field lab, gas chromatograph fitted with electron capture and flame ionisation detectors for $N_2O$ and $CH_4$. 
Seasonal profiles of $N_2O$ emissions

- Episodic nature of denitrification
- Treatments imposed, e.g. timing of N inputs, formulations of fert N, to explore mitigation options
- Data from such studies also aggregated to determine emissions factors (EFs) to be used in C accounting
- EF (IPCC 2006) default 1.0%, Australia 0.2%

Greenhouse gas emissions for wheat, canola and field pea

- Total GHG emissions determined using Life Cycle Assessment (LCA)
- Emissions of N$_2$O est. using EF of 0.2% (Aust Govt 2015)
- Emissions highest for N-fertilised canola and lowest for N$_2$-fixing field pea
- Differences related to fertiliser N inputs
  - Canola 100N
  - Wheat 60N
  - Field pea 0N (100N fixed)
- Soil C changes not included

Legume fixed N is not free....

- 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))

<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>0.90</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>

Legume fixed N is not free....

- 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 after 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</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–wheat</td>
<td>1350</td>
<td>+146</td>
<td>1204</td>
</tr>
<tr>
<td>Canola–wheat</td>
<td>1517</td>
<td>+1136</td>
<td>380</td>
</tr>
<tr>
<td>Field pea–wheat</td>
<td>1114</td>
<td>-366</td>
<td>1480</td>
</tr>
</tbody>
</table>
Concluding statements

- Nitrogen-fixing legumes may have benefits for environmental impact categories such as fossil fuel energy demand, eutrophication potential etc 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 a 13.8 kg DM loss/kg N fixed (equivalent to 5.5 kg C or 20 kg CO$_2$/kg N fixed). This direct cost is not factored into GHG emissions accounting.
- The loss of legume DM translates into reduced residue C returned to the soil after grain harvest and reduced incorporation of C into soil OM. Simple modelling of field pea (100N fixed) and canola (100N as fertiliser) indicate a difference in soil C stocks during 12-month period of 460 kg C/ha = 1680 kg CO$_2$ in favour of canola, substantially changing the LCIs.
- There may be little overall impact of the C cost of N$_2$ fixation on grain production because evidence that N$_2$-dependent legumes produce grain more efficiently than mineral N-dependent legumes, i.e. > HI and NHI.