Potential of Legumes

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Background and context ....

• Lack of forage protein (BSE-crisis, big imports)
• Product quality: traceability, home grown
• Increasing costs for energy and N-fertiliser
• Emissions from agriculture
• Restrictions in resource input
• Growing demand for meat and milk
…. lead to sustainable intensification

- Presently (the) headline in agriculture
- More yield needed ⇔ less resources available
- Only solution is to increase efficiency
  - *More* yield/quality with the *same* input/emissions
  - *Same* yield/quality with *less* input/emissions
  - *More* yield/quality with *less* input/emissions
Legumes a key to increase efficiency

- **MultiSward** | **J.L. Peyraud** (INRA, Rennes)
  www.multisward.eu

- **LegumePlus** | **I. Mueller-Harvey** (University Reading)
  www.legumeplus.eu

- **Legume Futures** | **R.M. Rees** (SRC, Edinburgh)
  www.legumefutures.eu

- **Animal Change** | **J.F. Soussana** (INRA, Clermont-Ferr.)
  www.animalchange.eu

- Many thanks to Jean-Louis, Irene, Bob and Jean-François
Selected key topics

1. Legume-grass mixtures for high yields
2. Symbiotic N$_2$ fixation
3. High forage quality for high animal production
4. Plant secondary metabolites a key feature
5. Climate change: mitigation and adaptation
6. Development and transfer of legume-grass mixtures
Objective

• Review opportunities legumes offer
• State research needs and critical points
• Spot new technological opportunities
• Address transfer to practice
1. Legume-grass mixtures for high yields
COST 852 Agrodiversity Experiment

Objectives
Fertile agricultural sites
Species richness (low levels) 1, 2, 4 species
Species proportion (focus to optimise): 100%, 90%, 70%, 50%, 40%, 25%, 10%, 3%, 0%

Methods
Simplex design
31 sites, 17 countries, 1‘200 plots, thank you all!
Species examined

Best forage species
4 functional types
(factorial combination of)
- grass / legume
- fast / slow

Example for Nordic sites
- Grass fast: *Ph. pratense*
- Grass slow: *P. pratensis*
- Legume fast: *T. pratense*
- Legume slow: *T. repens*
Strong and persistent yield advantage of mixtures

Finn et al. (2013)
Strong and persistent yield advantage of mixtures

Total yield

98% of Mix plots > average Mono
65% of Mix plots > best Mono

Finn et al. (2013)
Clover proportion matters, but very broad range of mixture advantage

Nyfeler et al. (2009)
Other experiments: basis of comparison

**Average monoculture**

- **Mixture yield:** +77%

- **Cardinale et al.** (2007)

**Best monoculture**

- **Mixture yield:** -12%

- **Trangressive overyielding**

Cardinale et al. (2007)
Other experiments: basis of comparison

**Average monoculture**

- Yield mixture: +77%

**Best monoculture**

- Yield mixture: -12%

Most papers report positive diversity effects, i.e. higher yield than average monoculture - BUT NOT - higher yield than best monoculture

Cardinale et al. (2007)
What is so ‘special’ with COST 852? How to design mixtures for production?

![Graph showing yield vs. clover proportion]

- **Best monoculture**
- **Average monoculture**
- **COST 852**
- **Average monoculture 50% of best mono**

Cardinale *et al.* (2007)

Nyfeler *et al.* (2009)
What is so ‘special’ with COST 852? How to design mixtures for production?

1. All species high yielding:
   - Best four species selected

2. Maximised diversity effect
   - legume / grass
   - fast / slow

Nyfeler et al. (2009)
Challenges

• Develop productive mixtures
• Develop mixtures with a stable legume content
• Continuously adapt these mixtures to the ongoing changes (breeding, management, climate)
• Simplex design a powerful tool for multidimensional optimisation
• Transfer mixtures into farming systems and industry (seed companies)
2. Symbiotic $N_2$ fixation
Symbiotic $N_2$ Fixation (the) key of legumes

Industry, Haber-Bosch

For production of 1 kg fertiliser-$N$
- 2 l oil
- 2.25 kg CO$_2$
- 9.8 g N$_2$O
$\Rightarrow$ 8.6 kg CO$_2$-equivalents

Symbiosis, Sun-Energy

Energy (Carbohydrates)

Nitrogen (Amino acids)
N₂-fixation: mixtures especially efficient

- Mixtures with 40-60% clover fixed the same amount as clover monocultures

Nyfeler et al. (2011)
Energy proofing by symbiotic $N_2$-fixation

- Productive grass-clover mixtures fix about 200 kg N ha$^{-1}$ yr$^{-1}$
- This corresponds to the fuel needed to drive 10‘000 km with a small car
### Altitudinal gradient and % Nsym

**Optimum pH**

6.5 – 7.0

<table>
<thead>
<tr>
<th>Altitude</th>
<th>900</th>
<th>1400</th>
<th>1900</th>
<th>2100</th>
<th>2300</th>
<th>2600</th>
<th>2800</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>5.6</td>
<td>4.6</td>
<td>4.1</td>
<td>4.1</td>
<td>-</td>
<td>-</td>
<td>3.1</td>
</tr>
<tr>
<td>°C Veg</td>
<td>13</td>
<td>12</td>
<td>9</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>3</td>
</tr>
</tbody>
</table>

Reykjavik

Jacot *et al.* (2000a, 2000b)
Altitudinal gradient and % Nsym

Lot. corn. / alp. ........................................... 79%
Trif. pra. / niv. ........................................... 79%
Trif. repens ........................................... 70%
Vic. sativa ........................................... 82%
Trif. thalii ........................................... 79%
Trif. badium ........................................... 84%
Trif. alpinum ........................................... 91%

Altitude  900  1400  1900  2100  2300  2600  2800
pH  5.6  4.6  4.1  4.1  -  -  3.1
°C Veg  13  12  9  7  -  -  3

Jacot et al. (2000a, 200b)
Clover is flexible: it regulates $N_2$ fixation to cover its N demand

- Mineral N decreases % N from symbiosis
- Grass partner stimulates % N from symbiosis

Nyfeler et al. (2011)
Positive implications for N losses

• If mineral N is available legumes down-regulate their fixing activity
  => Prevents excessive N input
• Grasses in the mixture efficiently deplete available N from the soil
  => Mineral N is not accumulated in the soil
• $\text{N}_2$ is fixed within the legume plant nodule
  => In contrast to fertiliser N, fixed N is not available in reactive form in the soil
N-fertiliser replacing potential

- Well balanced mixtures at N50 can be as productive as grass monocultures at N450

Nyfeler et al. (2009)
Summary

Nyfeler et al. (2009) found that using higher nitrogen inputs, such as N150 and N450, results in the same yield compared to using lower nitrogen inputs, such as N50. This indicates that it is possible to achieve the same yield with less input.
Summary

more yield with same input

Nyfeler et al. (2009)
Summary

Nyfeler et al. (2009)

more yield with less input

Yield year 2 (t DM ha\(^{-1}\) Yr\(^{-1}\))

Legume proportion year 1
Summary

more yield with less input
and with lower emission risk

NO$_3$-N (mg / L)

Nyfeler (unpublished)
Challenges

• Substantial legume proportion needed to fix big amounts of atmospheric nitrogen => same challenges as for mixtures
• Increase legume proportion in unsown grassland
• Study other legume species
• Functioning of symbiotic $N_2$ fixation at unfavourable conditions (P deficiency, …)
3. High forage quality for high animal production
Voluntary intake of legumes is greater than that of grasses

- The case for fresh, hay and silage
- Lower resistance to chewing, higher rate of particle breakdown, digestion and clearance from rumen
Nutritional quality of legumes decreases much less with ageing

This makes mixed swards easier to manage

<table>
<thead>
<tr>
<th>Rate of decline</th>
<th>Grasses</th>
<th>White clover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voluntary intake (kg / d)</td>
<td>-0.2</td>
<td>-0.1</td>
</tr>
<tr>
<td>Digestibility (unit / wk)</td>
<td>-0.02</td>
<td>-0.01</td>
</tr>
</tbody>
</table>

INRA (2007)
Clover increase production and fatty acide composition

Dairy cows

<table>
<thead>
<tr>
<th>2 experiments</th>
<th>PRG</th>
<th>PRG+RC</th>
<th>PRG+WC</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM intake (kg/d)</td>
<td>12.0</td>
<td>14.3</td>
<td>14.4</td>
</tr>
<tr>
<td>Milk yield (kg/d)</td>
<td>26.2</td>
<td>29.2</td>
<td>32.4</td>
</tr>
<tr>
<td>Fat content (g/kg)</td>
<td>42.8</td>
<td>41.3</td>
<td>39.6</td>
</tr>
<tr>
<td>Protein content (g/kg)</td>
<td>31.5</td>
<td>30.6</td>
<td>31.9</td>
</tr>
<tr>
<td>18:3 n-3 (g/100g fat)</td>
<td>0.42</td>
<td>1.00</td>
<td>0.94</td>
</tr>
</tbody>
</table>

PRG: perennial ryegrass
RC: red clover
WC: white clover

Dewhurst et al. (2003)
Protein feeding value of legumes

- Level of metabolisable protein of fresh forage is at recommended level for intensive production
- Supply of degradable N is always too high

INRA (2007)

Fresh forages
Silage
Hays

Fresh forages
Silage
Hays

g PDIN / UFL

metabolisable protein (g PDIE / UFL)

degardable protein

60
80
100
120
140
160
180
200

60
80
100
120
140
160

LUC
LUC
LUC
RC
RC
RC
PRG
PRG
WC
PRG

PRG
PRG
PRG

MultiSward
LegumePlus
Animal Exchange
Legume Futures
## Nitrogen flow in dairy cows

<table>
<thead>
<tr>
<th></th>
<th>PRG</th>
<th>WC</th>
</tr>
</thead>
<tbody>
<tr>
<td>N intake (g/kg DM)</td>
<td>26.1</td>
<td>38.5</td>
</tr>
<tr>
<td>Duodenal N flow (g/kg DM)</td>
<td>24.3 (93)</td>
<td>28.9 (75)</td>
</tr>
<tr>
<td>Ruminal N losses (g/kg DM)</td>
<td>1.8</td>
<td>9.6</td>
</tr>
<tr>
<td>Urinary N (g/kg DM)</td>
<td>20.1</td>
<td>29.1</td>
</tr>
<tr>
<td>N-excretion (g/kg milk)</td>
<td>17.0</td>
<td>20.7</td>
</tr>
</tbody>
</table>

- More N excreted => higher risk for N losses

Peyraud (1993), Ribeiro-Filho et al. (2005)
## Annual N flow for 3 dairy farmlets

<table>
<thead>
<tr>
<th></th>
<th>Farmlet 1</th>
<th>Farmlet 2</th>
<th>Farmlet 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stocking rate (cows/ha)</td>
<td>3.3</td>
<td>3.3</td>
<td>3.3</td>
</tr>
<tr>
<td>Inputs: fert N</td>
<td>0</td>
<td>215</td>
<td>413</td>
</tr>
<tr>
<td>N2 fixation</td>
<td>174</td>
<td>117</td>
<td>40</td>
</tr>
<tr>
<td>Others</td>
<td>5</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Outputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milk + meat</td>
<td>80 (45%)</td>
<td>95 (30%)</td>
<td>98 (22%)</td>
</tr>
<tr>
<td>Harvest forages</td>
<td>1</td>
<td>15</td>
<td>28</td>
</tr>
<tr>
<td>Transferred excreta</td>
<td>57</td>
<td>78</td>
<td>84</td>
</tr>
<tr>
<td>N surplus</td>
<td>41</td>
<td>150</td>
<td>248</td>
</tr>
<tr>
<td>Denitrification</td>
<td>5</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Volatilisation</td>
<td>16</td>
<td>38</td>
<td>61</td>
</tr>
<tr>
<td>Leaching</td>
<td>40</td>
<td>79</td>
<td>150</td>
</tr>
</tbody>
</table>

Ledgard, Penno and Sprosen (1999)
Challenges

• Prevent N-losses from animals due to the high content of degradable protein of legumes
  • High sugar grass
  • High sugar legumes
  • Plant secondary metabolites (PSM)
• High quality silages
4. **Plant secondary metabolites a key feature**
Plant secondary metabolites (PSM)

- All plants contain PSM
- PSM have many functions
- **Legumes are especially rich in PSM**
- PSM are complex, diverse and highly variable
  - Condensed tannins (CT)
  - Hydrolysable tannins, lignin, flavonoids, isoflavons, saponins, essential oils
Some legumes are especially rich in CT

- Big trefoil (*Lotus pedunculatus*)
- Sainfoin (*Onobrychis viciifolia*)
- Birdsfoot trefoil (*Lotus corniculatus*)
- Sulla (*Hedysarum coronatum*)

Our main legumes are low in CT

Sainfoin (sain=healthy, holy; foin=hay) seems the most promising candidate

Typical contents are 1 - 3% CT
CT mitigate methane emission

- **High variability** at low CT levels
- **High CT levels needed**

Jayanegara et al. (2012)
CT can mitigate $\text{N}_2\text{O}$ emission

Mueller-Harvey (2006); Scharenberg et al. (2007)
CT have anthelmintic properties

<table>
<thead>
<tr>
<th>Larval assay</th>
<th>Inhibition caused by sainfoin extracts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feeding</td>
<td>2 to 50 %</td>
</tr>
<tr>
<td>Migration</td>
<td>0 to 48 %</td>
</tr>
<tr>
<td>Exsheathment</td>
<td>0 to 82%</td>
</tr>
</tbody>
</table>

- **High variability**

Manolaraki (2011); Saratsis et al. (2012);
Novobilský et al. (2013); Desrues et al. (2013)
Where does this unreliability come from? or
The black box of CTs

Flavonoids

Hump = CTs, hundreds of peaks
CTs are highly complex and highly variable

CTs are polyphenols of different chain lengths
=> We can measure the mean length over all CTs (mDP)
CTs are highly complex and highly variable

PD: Prodelphinidin tannins
three OH groups

PC: Procyanidin tannins
two OH groups

cis
trans
CTs are highly complex and highly variable

PD: Prodelphinidin tannins
three OH groups

PC: Procyanidin tannins
two OH groups

Small changes in structure can have an important influence on the effect
## CT variability in Sainfoin

<table>
<thead>
<tr>
<th></th>
<th>among CV</th>
<th>within CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT content (%)</td>
<td>0.6 – 2.8</td>
<td>0.8 – 3.4</td>
</tr>
<tr>
<td>No of flavanol units (mDP)</td>
<td>12 – 84</td>
<td>n.a.</td>
</tr>
<tr>
<td>PDs (%)</td>
<td>53 – 95</td>
<td>55 – 90</td>
</tr>
<tr>
<td>Trans (%)</td>
<td>17 – 32</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

Stringano et al. (2012); Hayot Carbonero et al. (2011)
Malisch et al. (unpublished)
Challenges

• Reliability, predictability, stability (plant, animal, effect)
• Knowledge about the effects of different CTs (long vs. short chains; cis vs. trans; prodelphinidins vs. procyanidins)
• Big progress in analytical technique (mass spectroscopy)
5. Climate change: mitigation and adaptation
Legumes: An opportunity for mitigation of climate change

• Can reduce methane emission
• Can reduce nitrous oxide emission
• Reduce the use of fossil fuels (CO$_2$ emission)
• Support C-sequestration into soils
Adaptation: Legumes profit from elevated atmospheric CO$_2$

Yield response to elevated CO$_2$

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Swiss FACE Experiment

$L.\ perenne$ in mono +10%

$T.\ repens$ in mono +25%

$L.\ perenne$ in mix + 4%

$T.\ repens$ in mix +87%

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Lüscher et al. (2004)
Adaptation: Legumes profit from higher temperatures

- Clover proportion in mixture fluctuates with temperature

Lüscher et al. (2005)
Adaptation: Legumes seem to be especially drought resistant

Yield response to drought

<table>
<thead>
<tr>
<th>Experiment</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>L. perenne</em></td>
<td>-76%</td>
<td>-51%</td>
</tr>
<tr>
<td><em>C. intybus</em></td>
<td>-62%</td>
<td>-48%</td>
</tr>
<tr>
<td><em>T. repens</em></td>
<td>-34%</td>
<td>-29%</td>
</tr>
<tr>
<td><em>T. pratense</em></td>
<td>-21%</td>
<td>+3%</td>
</tr>
</tbody>
</table>

Hoekstra, Hofer, Suter, Finn, Lüscher (unpublished)
6. Development & transfer of legume-grass mixtures

• Introduce a new system might be difficult
• Example of a system that runs well
1) Forage plant breeding
2) Cultivar / species testing

- Sites 200 to 1850 m a.s.l.
- Conventional and organic
- 3 years field experiment
List of recommended cultivars

Yield

Persistence

Overwintering

Forage Quality

Disease Resistance
3) Mixture development on small plots
4) Mixture development on farms
List of Standard Mixtures
5) Quality label of the Swiss Grassland Society (AGFF)

- Guarantee high quality
  - best cultivars
  - best mixtures
  - best seed quality

- Easy recognition and correct selection of the mixture type
Participation is completely voluntary. Nevertheless, > 80% seeds sold with this quality label.

5) Quality label of the Swiss Grassland Society (AGFF)

- Guarantee high quality
- Guarantee best cultivars
- Guarantee best mixtures
- Guarantee best seed quality
- Easy recognition and correct selection of the mixture type

Nevertheless > 80% seeds sold with this quality label.
Conclusions

• Grass-legume mixtures combine the potential to reduce resource input with high plant and animal productivity and a low risk of environmental problems.

• Thus, grass-legume mixtures offer important opportunities to cope with the present and future challenges of agriculture.

• Challenges for research, development and transfer remain.
Thank you for your attention

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