Synthesis on the effects of grain legume insertion and cereal-grain legume intercrops in low input cropping systems in Southern France

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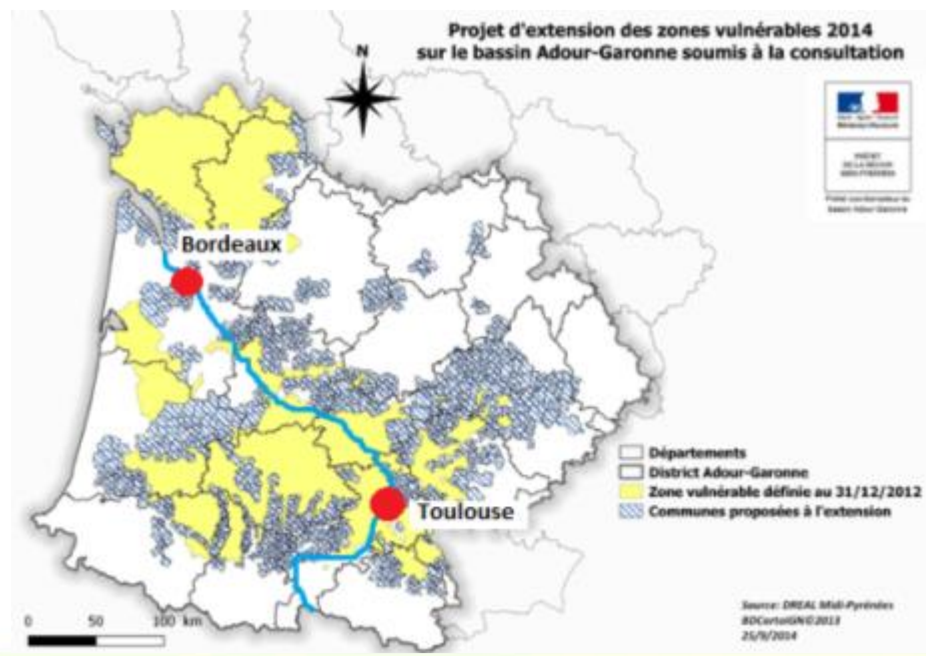
Introduction (i)

- *Garonne valley*: devoted to arable crops production (rainfed & irrigated)
- Traditional crop rotation: wheat – sunflower (9-10 months bare fallow)
- Farmers applied high N fertilization rates on Durum Wheat (for high protein content): **area declared vulnerable/sensitive to nitrate pollution**
- French national plan **for reducing pesticide use**: target of "minus 50%"
- **Legumes: a pillar towards the paradigm of agroecology** (Duru et al., 2015)



Introduction (ii) and main questions

The inclusion of legumes in arable cropping systems represents a good strategy to reduce current N fertilizer- dependency, reduce GHG emissions at cropping system level (local) and at global scale (e.g. Jensen et al., 2012). Crop diversification with legumes also contributes to a range of ecosystem services (e.g. Giller, 2001; Voisin et al. 2014).

Main questions investigated here:

1) Which are the **impacts** of the increase in the **use of grain legumes** in the arable rotations managed under conventional tillage **on**:
   - ✓ **Agronomic performances of the cropping system scale?**
   - ✓ **Soil organic carbon (SOC) and nitrogen (SON) dynamics?**
   - ✓ **N_2O emissions and GHG balance?**

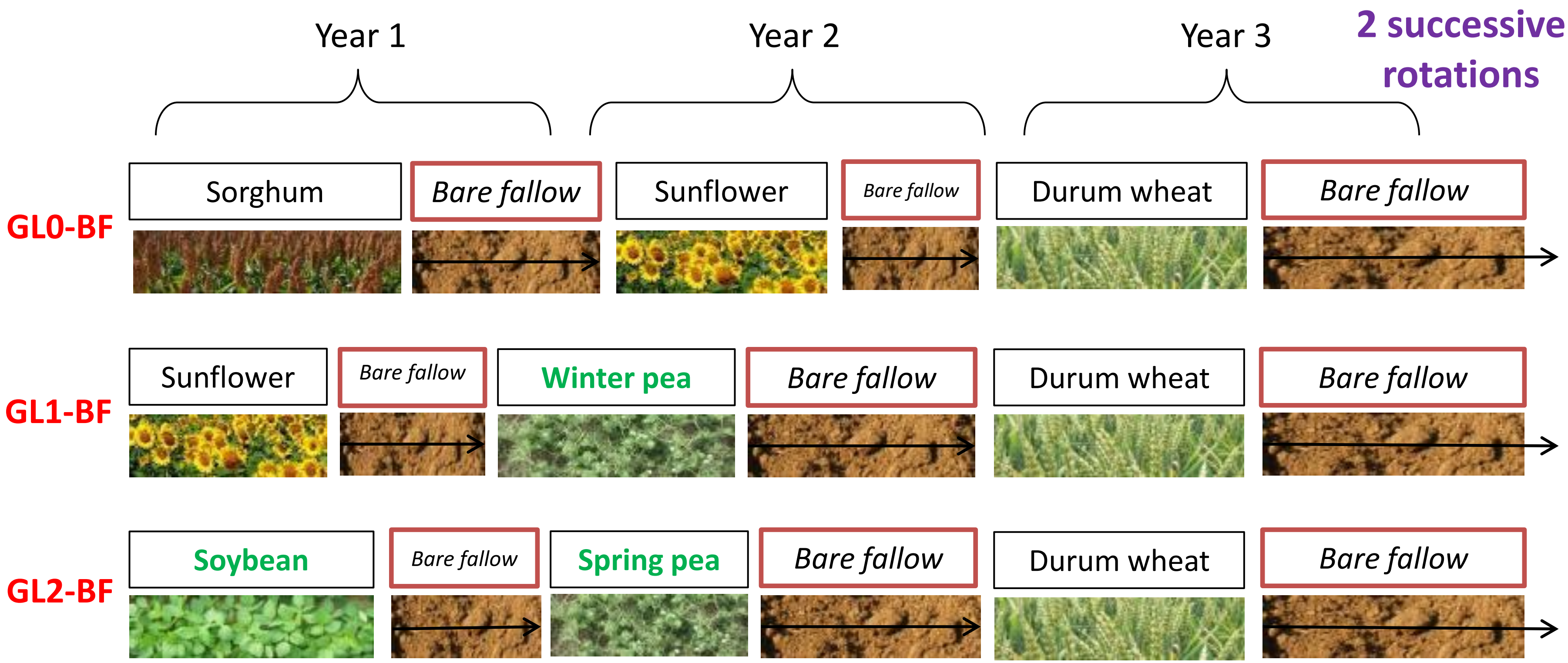
2) Which is the **role** played by the concomitant insertion of **cover crops** in legume-based arable systems on the key processes (N recycling)?

3) Is **intercropping** an efficient way to insert legumes in cropping systems?

Materials and methods: *i) Experimental design (INRA)*

Experimental design (LGBI established with the FP6 EU GLIP project / 2004-2010)

Establishment: 2003. Auzeville (SW France). Rainfall: 685 mm; Temperature: 13.7 ºC; PET: 905 mm
Split-plot design with three blocks. Subplot size: 200 x 15 m.
Soil (0-30 cm): pH: 7.0; organic C: 8.7 g kg^{-1}; clay-loam texture (37, 36 and 27% for sand, silt, clay)



GL0, GL1 and GL2: no, one and two grain legumes in a 3-year rotation
BF: bare fallow

Materials and methods: *i) Experimental design 2*

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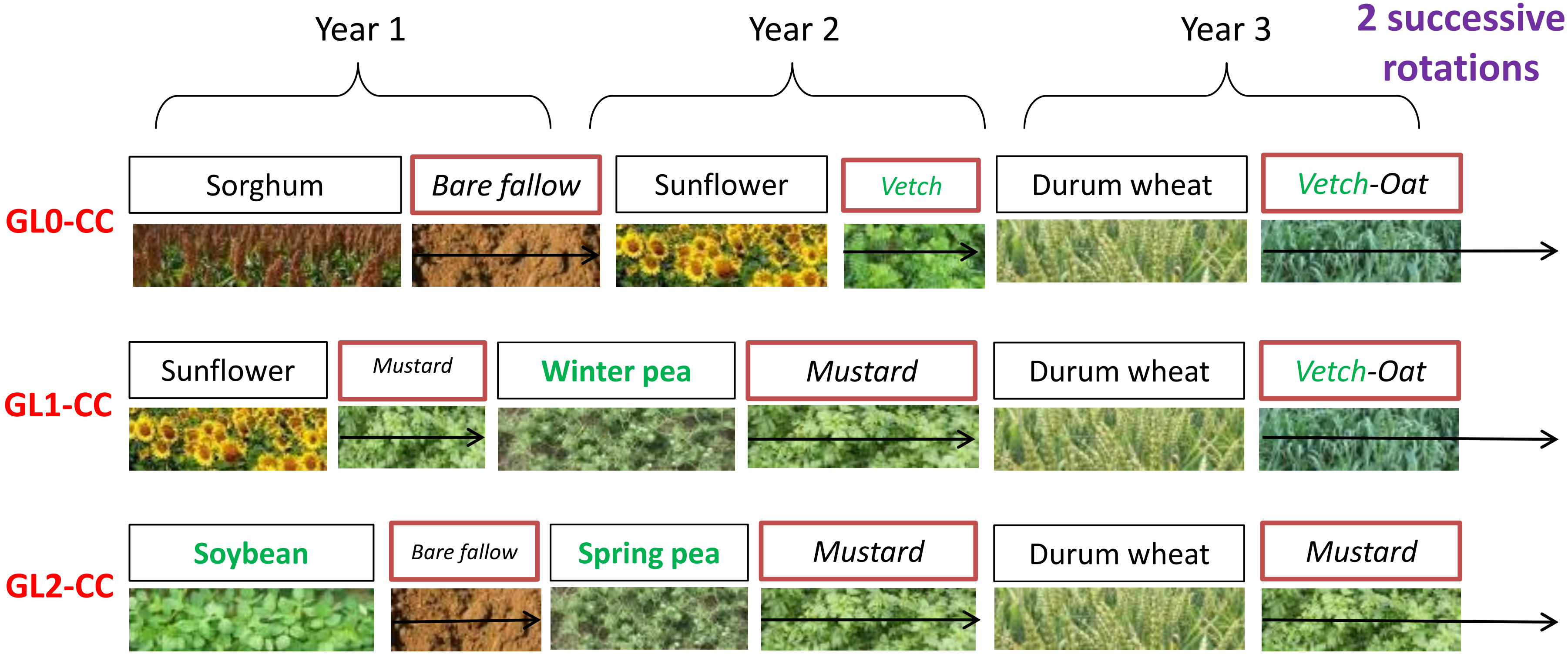


GL0, GL1 and GL2: no, one and two grain legumes in a 3-year rotation
BF: bare fallow

Materials and methods: *i) Experimental design 3*

- New experimental design called MicMac-design (2010-2016); AIM: To finally design agroecological prototypes of arable cropping systems
- And to improve the multicriteria analysis: soil/proxy air biodiversity (microbial analysis [DNA]+ macro-fauna)

2 other successive rotations

Year 1 | Year 2 | Year 3

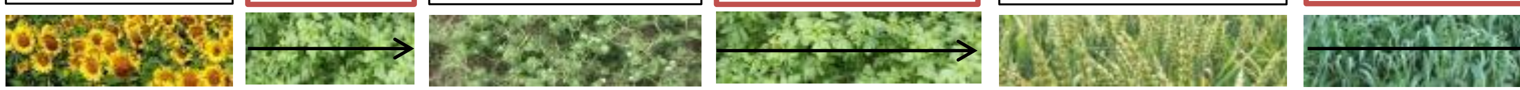
Low pesticides (- or + CC)

Sorghum | *Bare fallow* | Sunflower | *Clover* | Durum wheat | *Vetch-Phacelia*

Mixtures of 3 to 4 varieties (cultivars) per crop

Very low inputs (- or + CC)

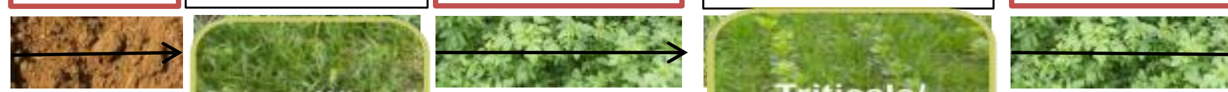
Sunflower | *Oat* | Faba bean | *Mustard-Faba* | Durum wheat | *Vetch-Oat*

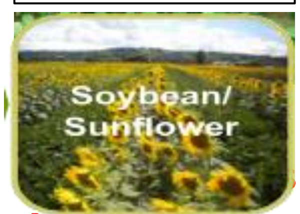


Mixtures of 2 species per crop cycle

Agroecology (- or + CC)

Sunflower-Soy. | *Bare fallow* | D.Wheat-Pea | *Mustard* | W.Wheat-Faba. | *Oat-Phacelia*





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...: strong red... icides (as much a... fertilizer-N

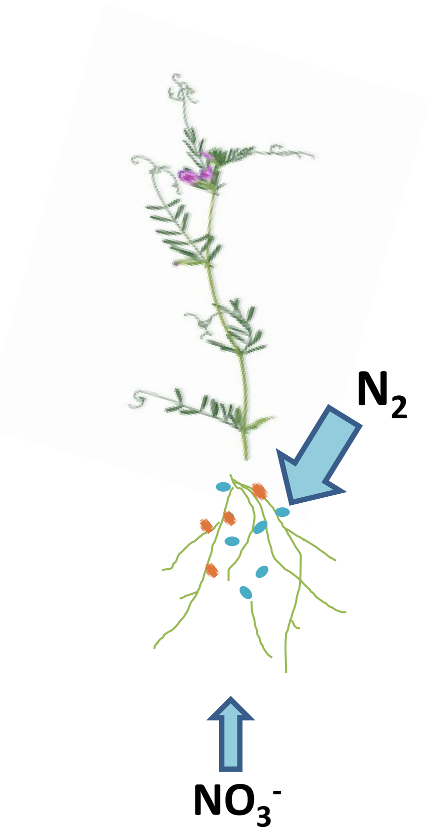
Agroecology: towards 0 pesticides and fertilizer-N, excluding seed pesticide treatments

Materials and methods: *ii) Protocol and measurements*

- **Crop management based on decision rules to adjust technical acts notably N applications to the soil, crop status and preceding crop**

- **Plant/crop and Soil samplings and analysis (all cash and cover crops)**

- **Biomass and Yield**
- **N uptake and N_2 fixation by legumes**
- **Soil water and mineral N**
- **Soil organic C and N**



Materials and methods: *iii) GHG measurements*

❖ N_2O samplings and analysis (2010-2016 only; 6 treatments/year)

- Automatic chambers and spectrometers (N_2O and CO_2 direct analysis) in field
- Daily "continuous" (4 times a day) measurements during crop cycle and fallow period

❖ Soil water potential and temperature in upper layers (-10 & -20 cm)

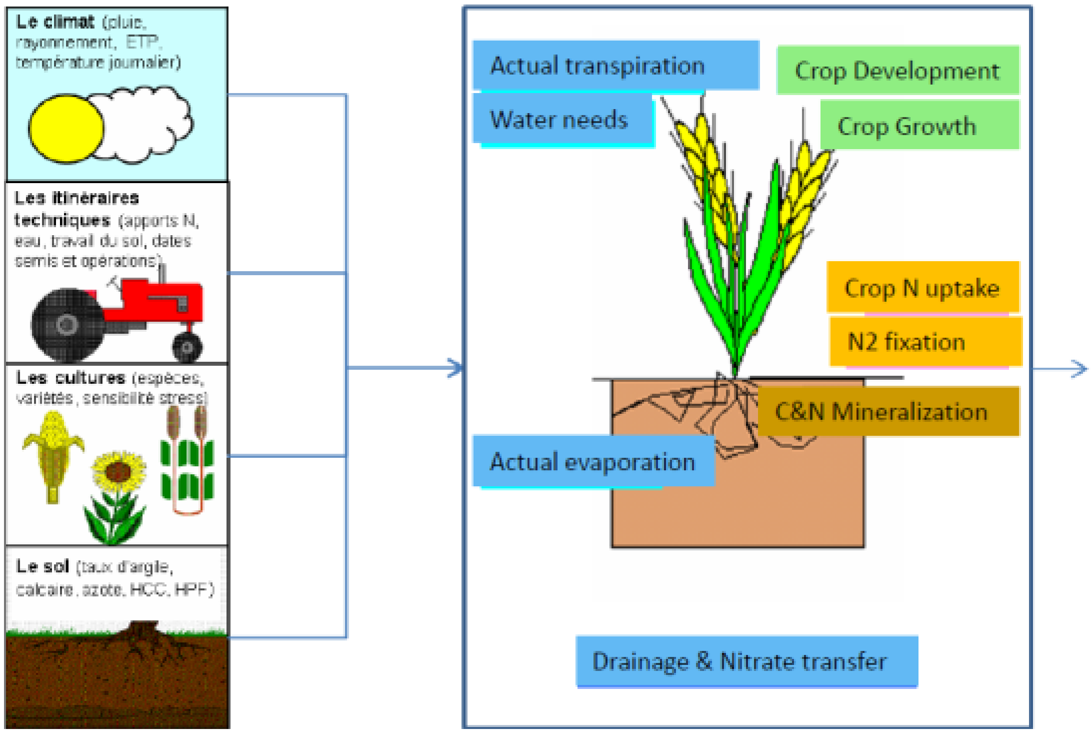
- Temperature sensors (measurements each 10 minutes)
- TDR sensors for water potential (measurements each 10 minutes)

Materials and methods : *iv) Modelling to complete data*

- **Calibration and validation of the STICS soil-crop model (Brisson et al. 1998, 2003; 2008) to simulate different soil and crop processes (Water-C-N budgets)**

Inputs | **Simulated processes** | **Outputs**

Wide range of crops and varieties



Soil water content
Soil mineral N
Biomass & Yield
N acquired
N_2 fixation
SOC & SON

N_2O emissions
NH_3 losses
Water drainage
NO_3 leaching &
NO_3 concentration

- **Version v8.3 validated for a wide range of species & sites (Coucheney at al., 2015)**
- **Modified for improving N_2O emissions (Bessou et al. 2010; Plaza-Bonilla et al., 2016)**

Main results: *5 take-home messages*

(from our INRA experiment in Toulouse)

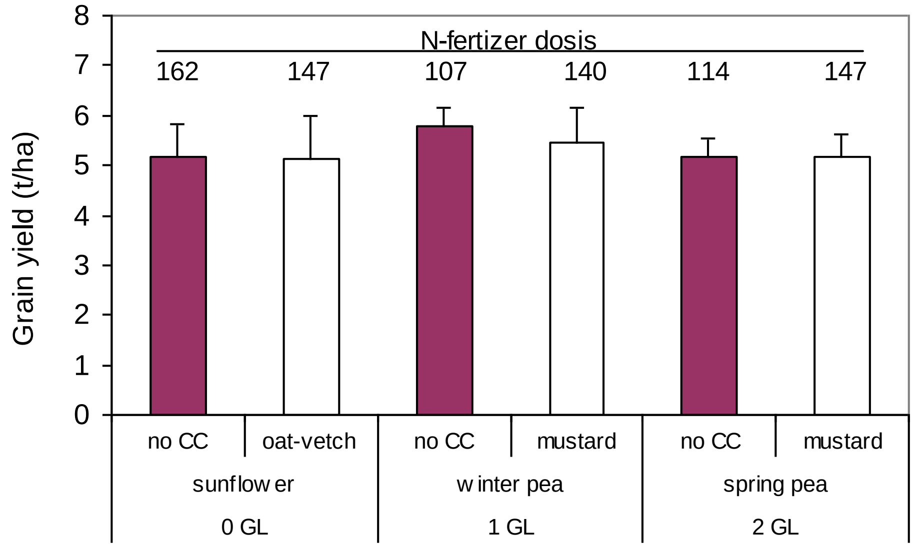
Projet MicMac–Design

Main results: 1) N balance and N preceding effect of G. legumes

Cropping system	Cash crop	N rate (kg N ha^{-1} yr^{-1})	Rotation N rate (kg N ha^{-1} 3 yr^{-1})	
GL0-BF	Sorghum	82	303	
	Sunflower	55		
	Durum wheat	166		
GL0-CC	Sorghum	82	295	
	Sunflower	55		
	Durum wheat	158		
GL1-BF	Sunflower	6	126	-58%
	Winter pea			
	Durum wheat	120		
GL1-CC	Sunflower	6	151	-49%
	Winter pea			
	Durum wheat	145		
GL2-BF	Soybean		117	-61%
	Spring pea			
	Durum wheat	117		
GL2-CC	Soybean		130	-56%
	Spring pea			
	Durum wheat	130		

pre-emptive competition in dry years

Yield of Durum Wheat (at the optimal fertilized N rate)



Durum wheat yield & fertilizer-N rate

- Yield of durum wheat higher after w. pea
- N release from CC residues not always compensate pre-emptive competition for soil mineral-N
- Rate of fertilizer-N must be sligtly increased after CC to reach the same yield

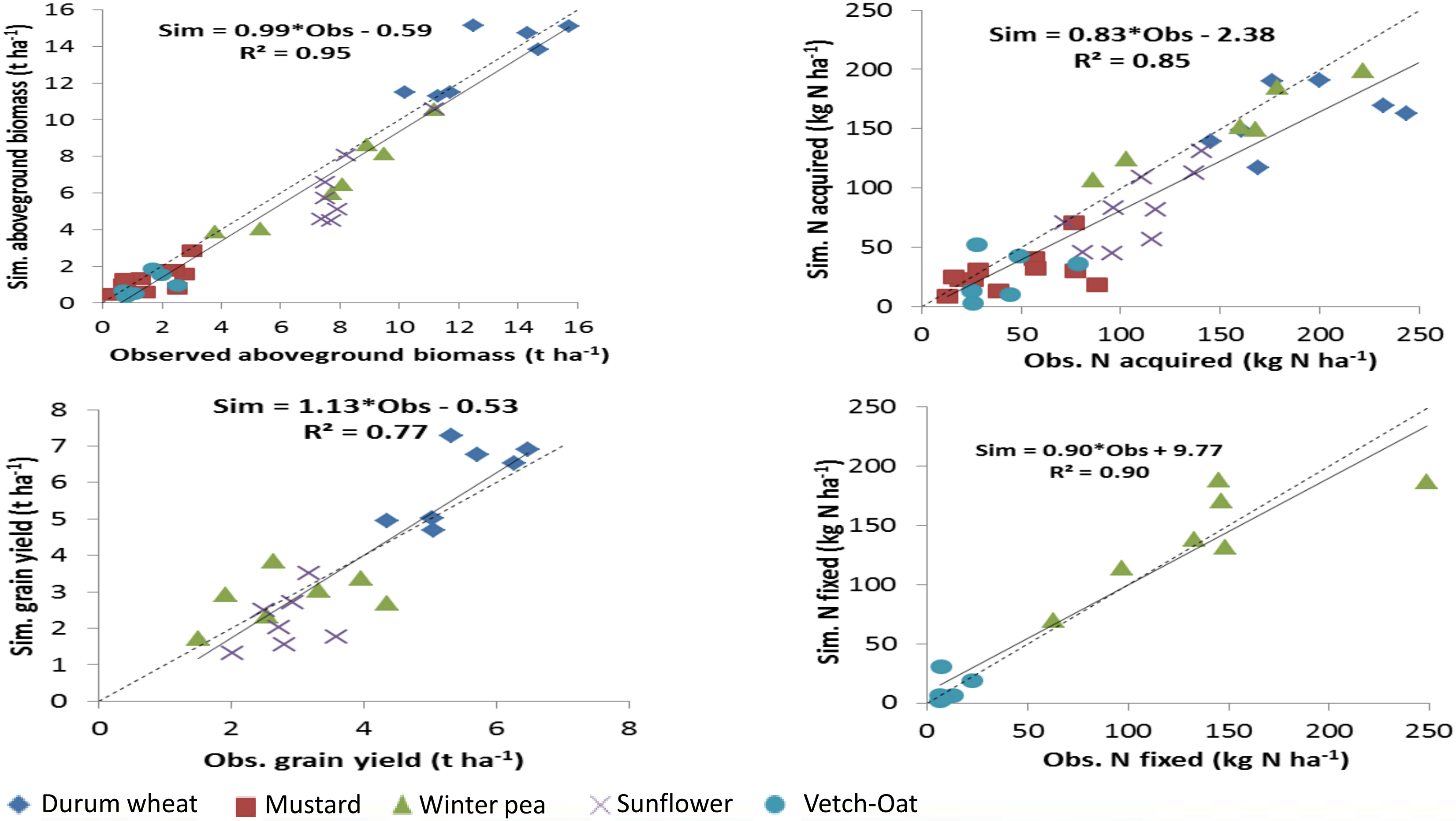
Plaza-Bonilla et al. (2015). Agri., Ecos. & Envir.

Main results: *5 take-home messages*

1) **Pea / Fababean as a preceding crop increased durum wheat grain production by 8% compared to sunflower as a preceding crop with a mean reduction of N fertilization of 45 kg N ha^{-1}. No effect of soybean vs cereal…**

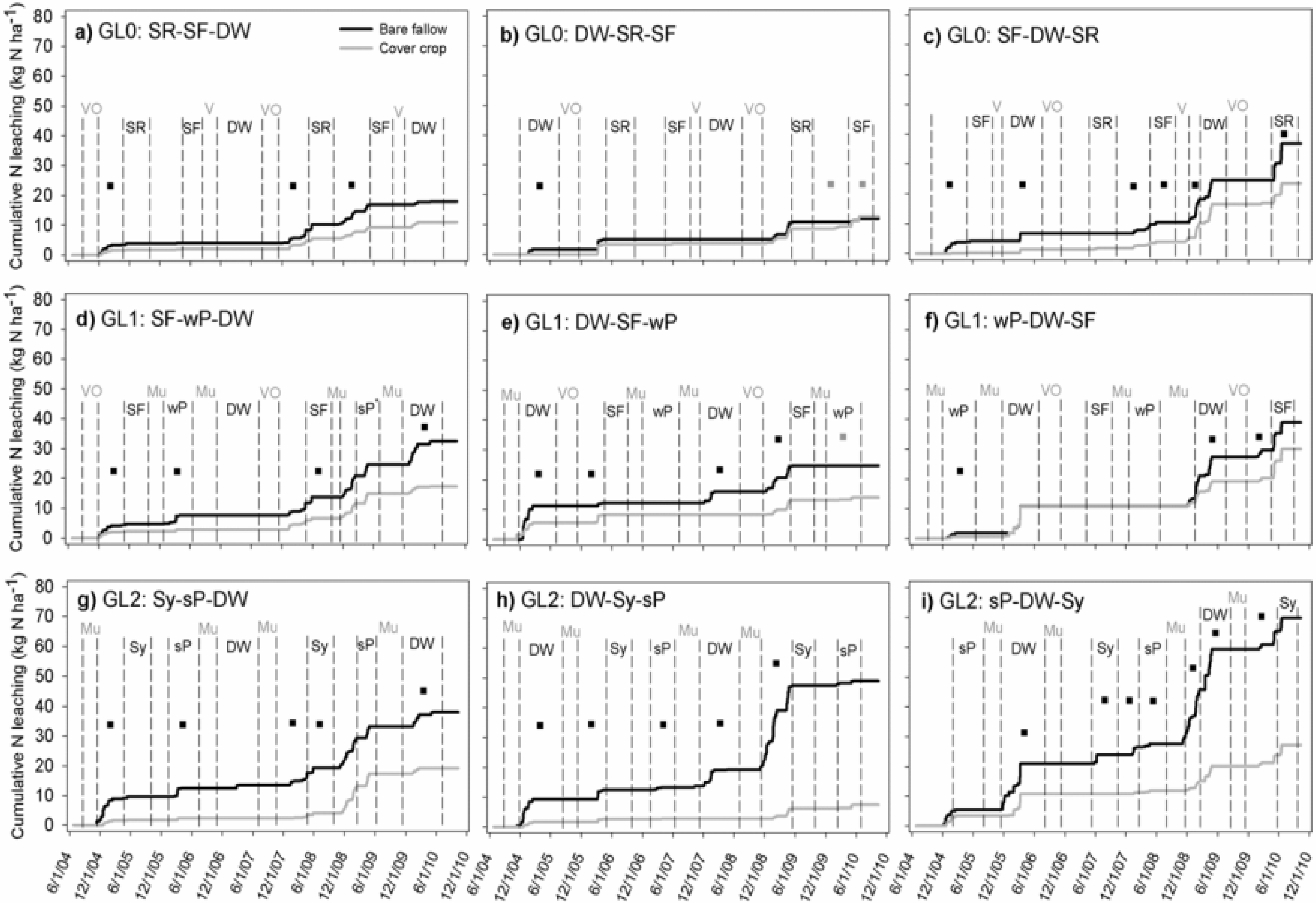
Main results: 2) STICS is relevant to simulate H_20-C-N- cycles

STICS soil-crop Model was found robust and accurate: allow to simulate water, C and N fluxes with a good confidence: outputs used to complete the field measurements



Plaza-Bonilla et al. (2015). Agri., Ecos. & Envir.

Cumulative nitrate leaching higher with legumes (rotation scale)



GL0 +CC

22 kg N-NO_3/ha

15 kg N-NO_3/ha

GL1 +CC

32 kg N-NO_3/ha

20 kg N-NO_3/ha

GL2 +CC

52 kg N-NO_3/ha

18 kg N-NO_3/ha

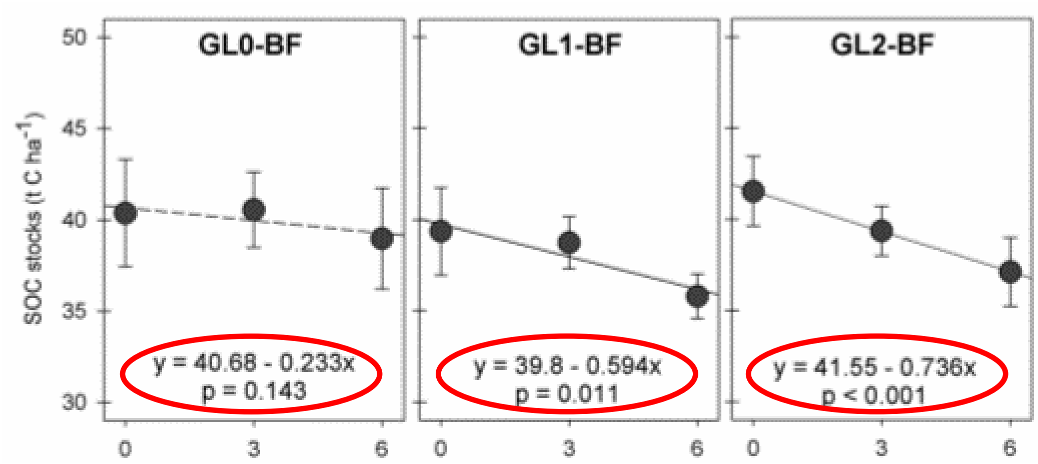
Plaza-Bonilla et al. (2015). Agri., Ecos. & Envir.

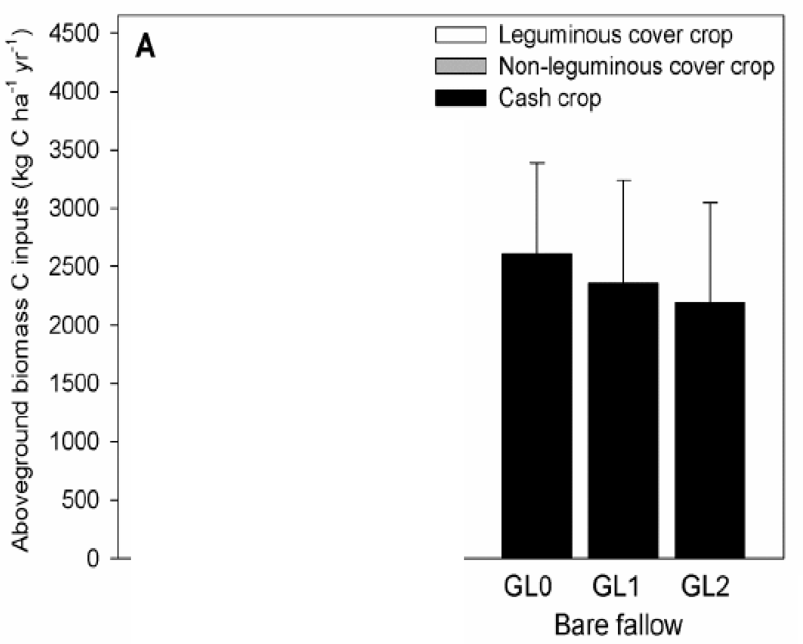
Main results: *5 take-home messages (our experiment…)*

1) Pea / Fababean as a preceding crop increased durum wheat grain production by 8% compared to sunflower as a preceding crop with a mean reduction of N fertilization of 45 kg N ha^{-1}. No effect of soybean vs cereal…
2) **NO_3 leaching simulated using the STICS model was higher when increasing the number of GL (from 22 to 52 kg N ha^{-1} after two rotation cycles of 6 years, for 0 to 2 grain legumes respectively).**

SOC stocks decreased with G. legumes (0-30 cm depth : plough layer)

- Using a mixed effects statistical model: random effect to intercept (differences between replications on initial SOC and SON) and fixed effect to slope.





Plaza-Bonilla et al. (2016). Soil Till. Res.

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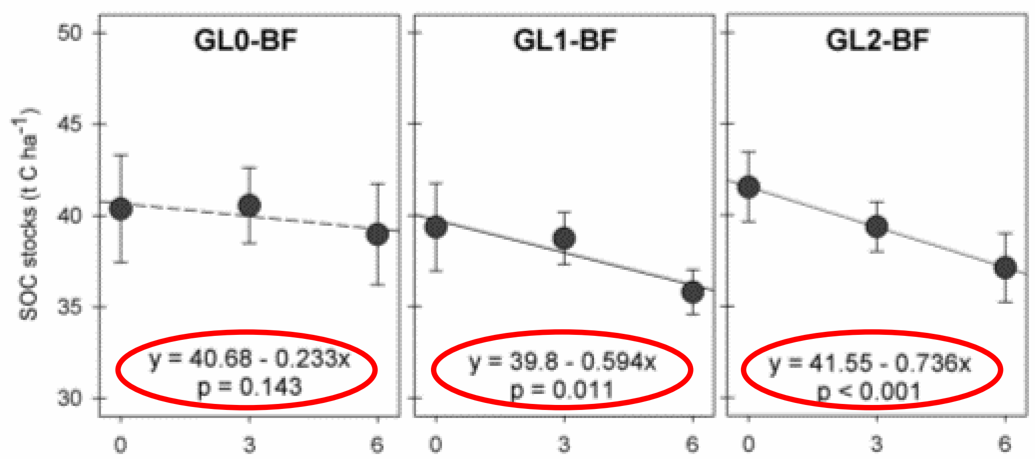
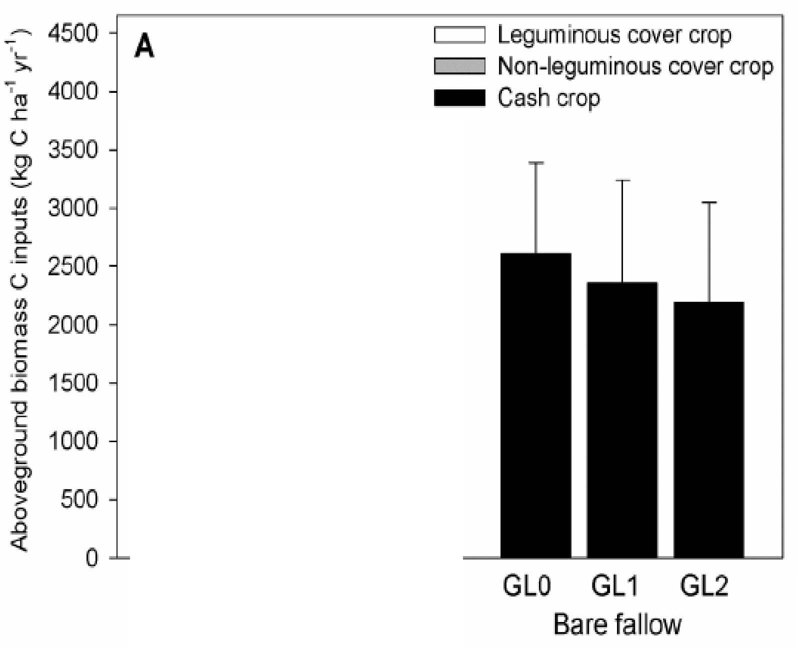
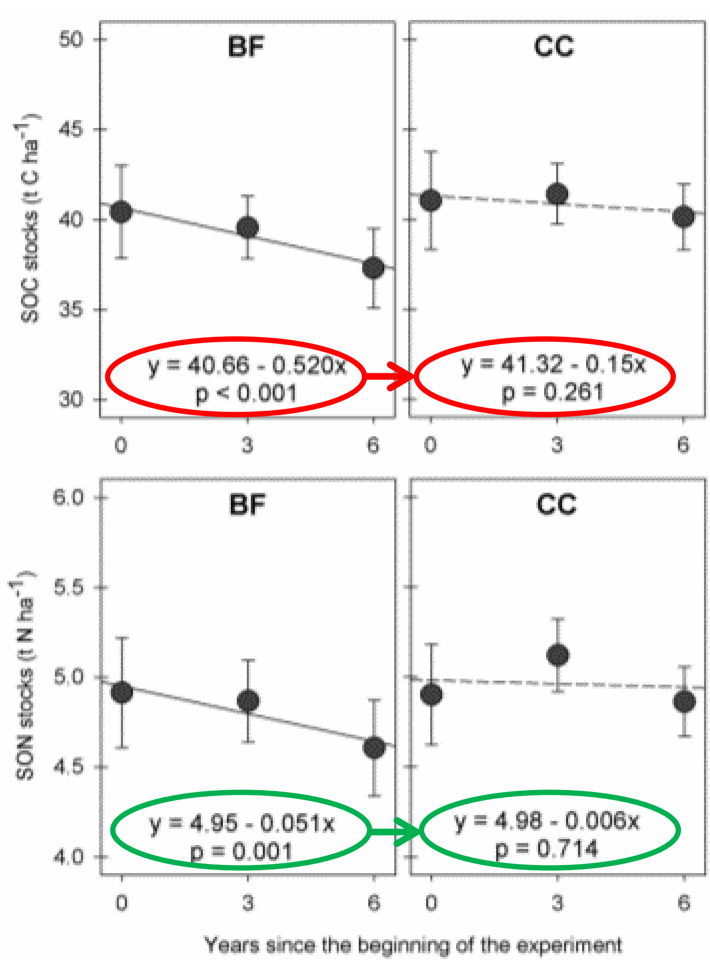




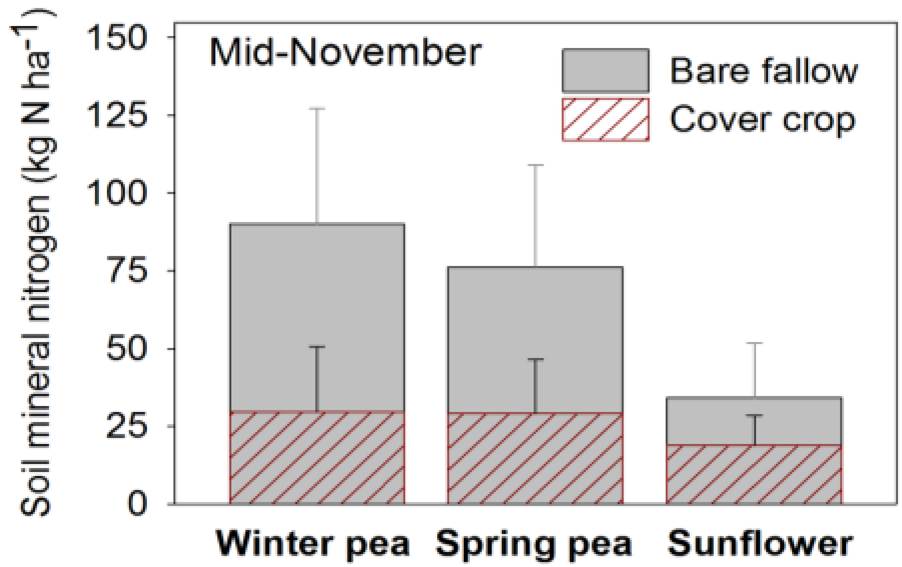
Plaza-Bonilla et al. (2016). Soil Till. Res.

Main Results: 4) Benefits of cover crops in legume-based rotations

Soil organic carbon (SOC) stocks



Soil organic nitrogen (SON) stocks



	Durum wheat (average 2005-2010)		
Cropping system	Grain yield (kg ha^{-1})	1000-grain weight (g)	Grain protein concentration (g 100 g^{-1})
GL0-BF	4974	41.3	13.8
GL0-CC	5012	41.4	13.8
GL1-BF	5458	41.5	13.8
GL1-CC	5296	43.2	13.7
GL2-BF	5282	41.3	14.0
GL2-CC	4991	42.0	13.9

Plaza-Bonilla et al. (2015; 2016). AGEE, STR

Main results: *5 take-home messages (our experiment…)*

1) Pea / Fababean as a preceding crop increased durum wheat grain production by 8% compared to sunflower as a preceding crop with a mean reduction of N fertilization of 45 kg N ha^{-1}. No effect of soybean vs cereal…
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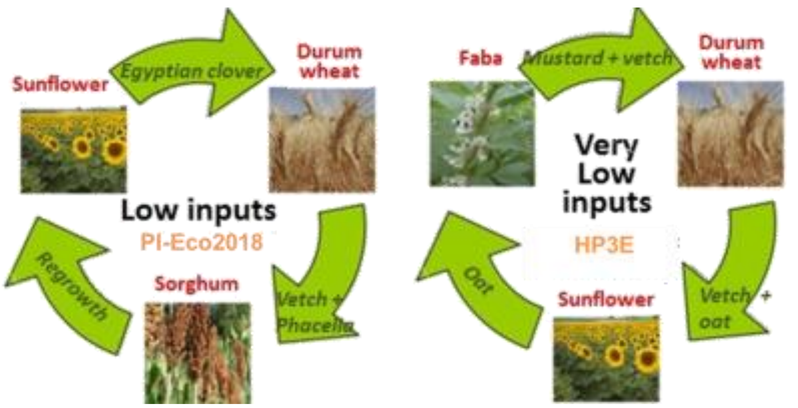
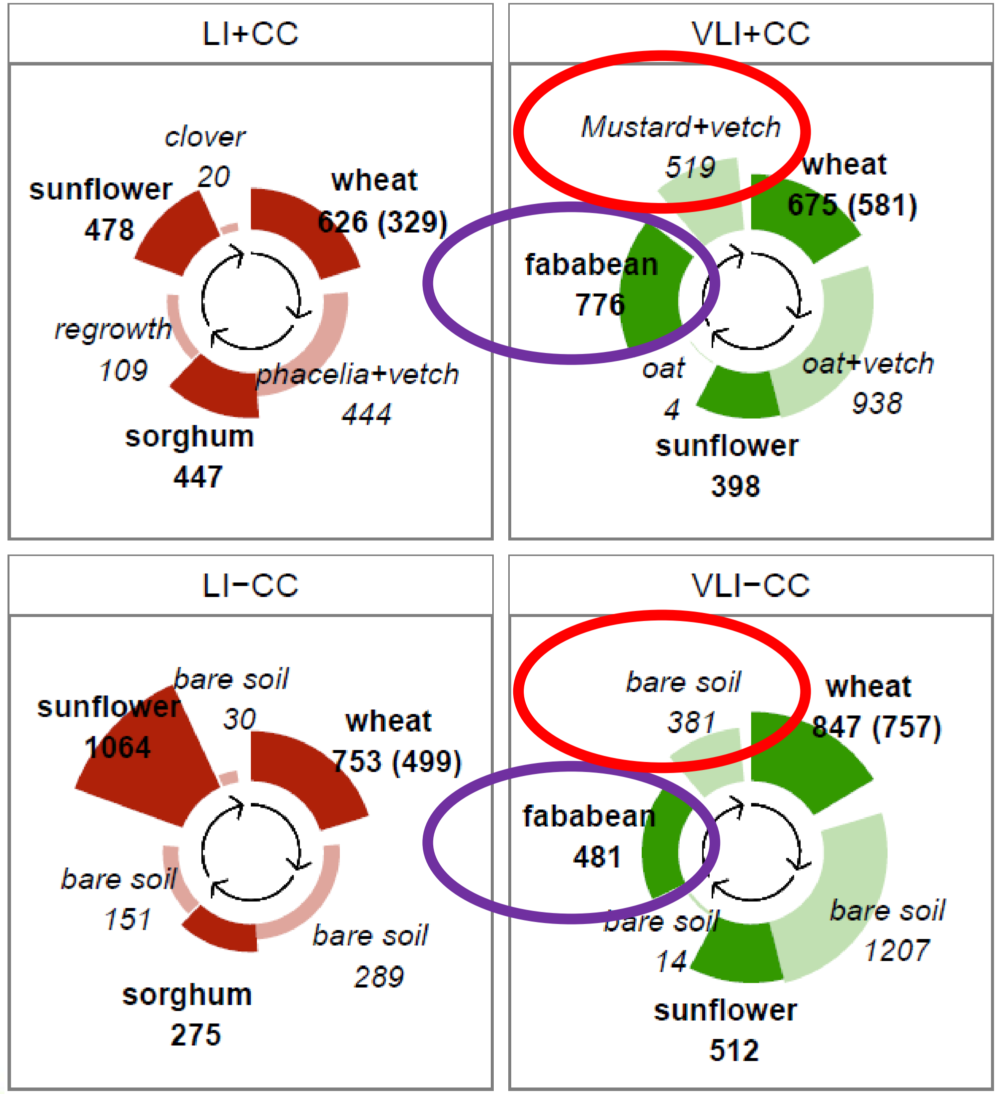
3) Inserting GL in the rotations significantly affected the amount of C and N inputs to the soil that were lower than with cereals and consequently led to a decrease in soil organic-C (SOC) and –N contents.
4) **However, Cover Crop insertion in legume-based cropping systems led to:**
    i. **reduced NO_3 leaching (from 15 to 18 kg N ha^{-1})**
    ii. **mitigated SOC loss, and**
    iii. **did not affect durum wheat grain protein concentration or yield.**

Main Results: 5) N_2O emissions with G. legumes

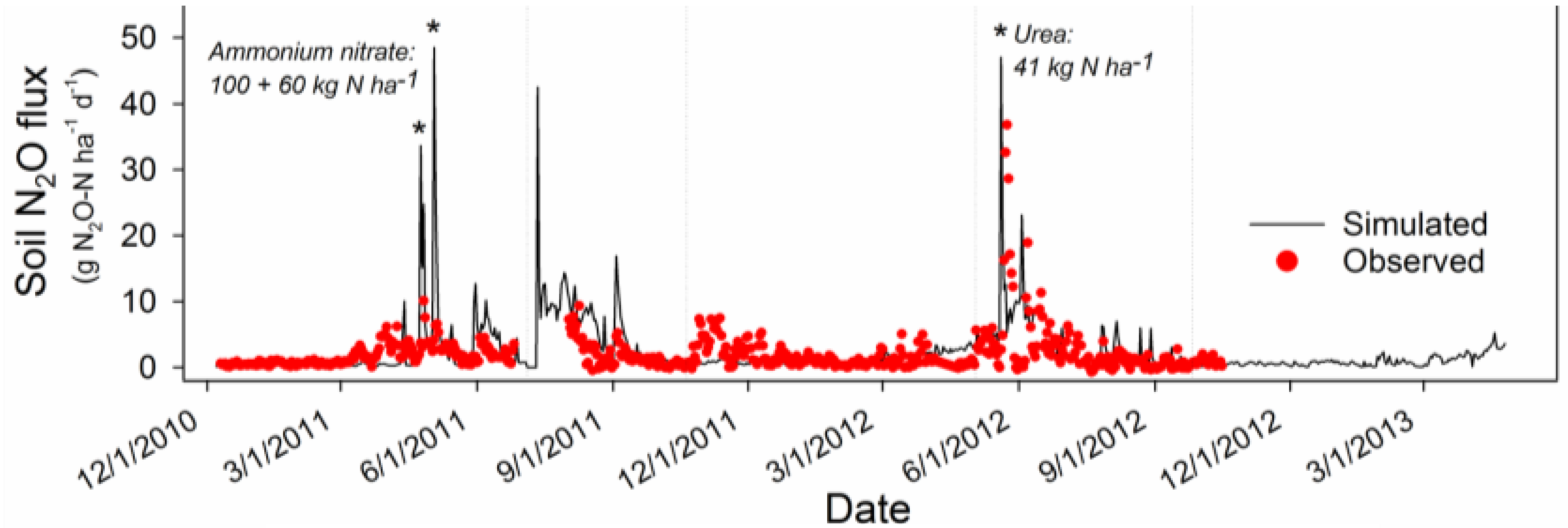


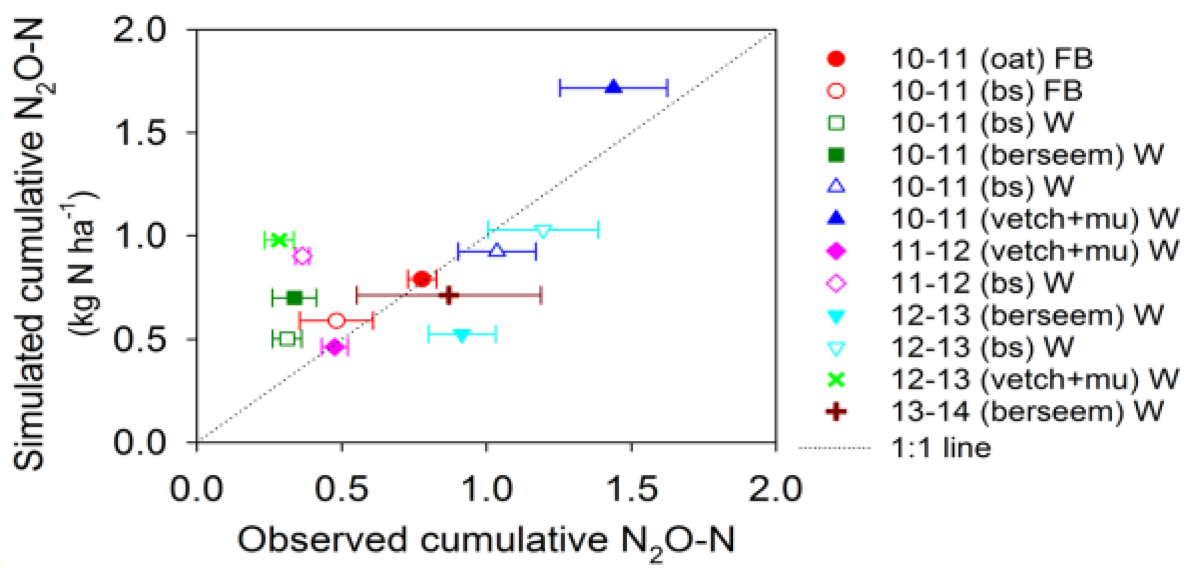


- ✓ N_2O emissions were low
- ➢ N_2O emissions during Faba bean crop cycle was lower than for other crops (i.e. durum wheat, sunflower)
- ➢ BUT, N_2O emissions after faba bean were higher than after cereal/sunflower
- ➢ Finally, N_2O emissions were significantly higher for VLI (with Faba bean) than for the LI (1.12 kg vs 0.78 kg N_2O -N ha^{-1} y^{-1})
- ➢ Fortunately, Indirect emissions are lower

Peyrard et al. (2016). Agri., Ecos. & Envir.

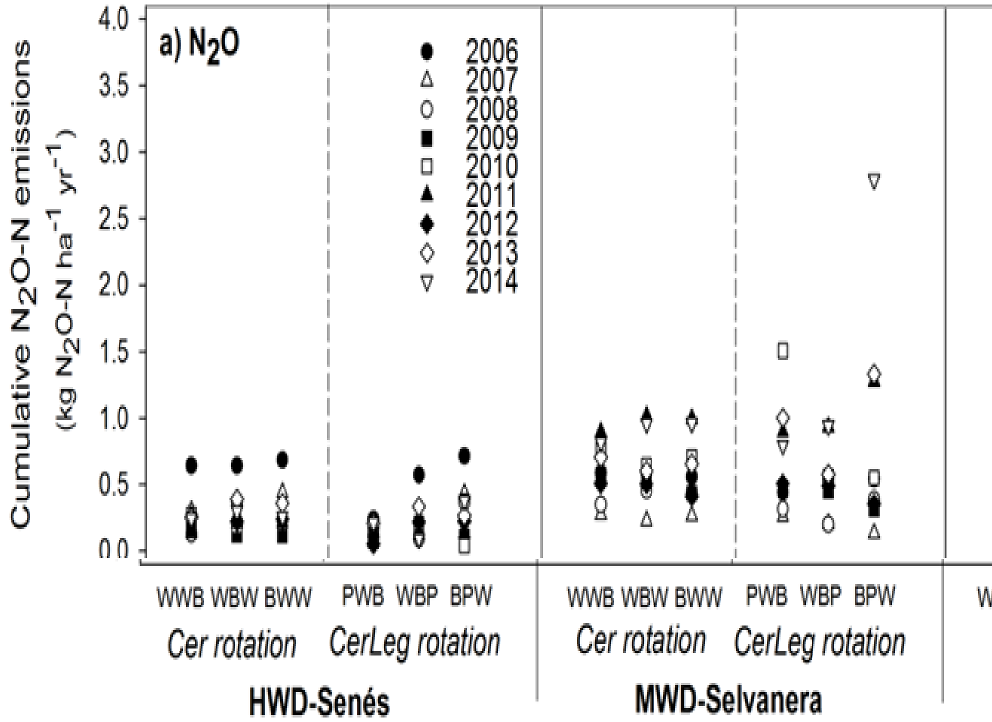
STICS, a satisfactory predictive model for N_2O emissions

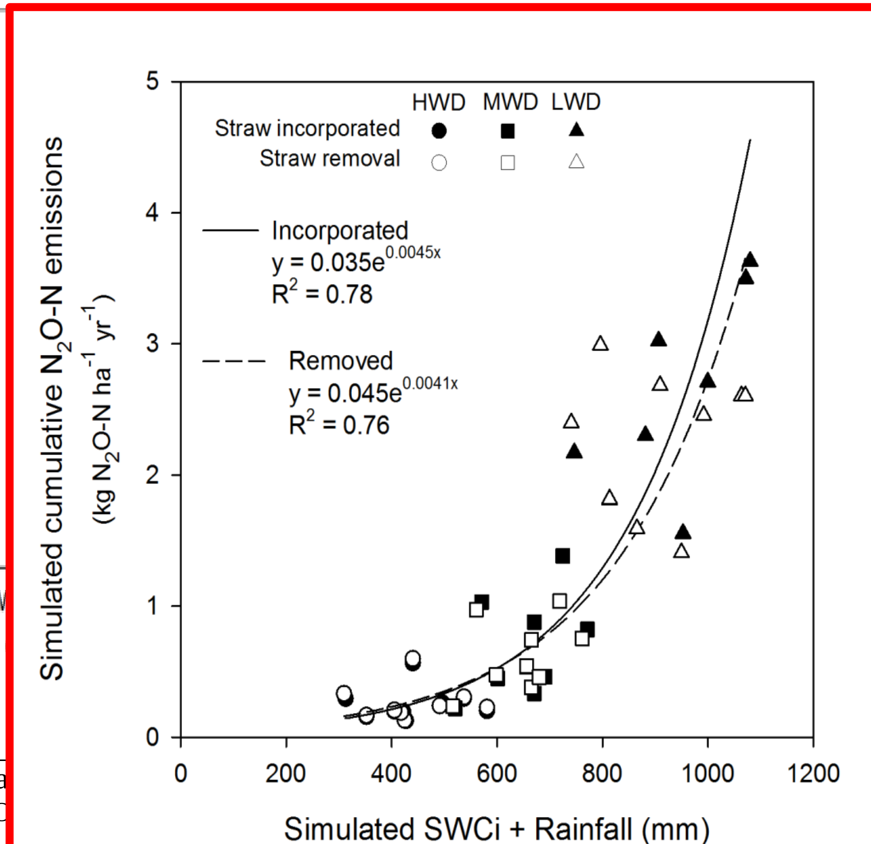




Plaza-Bonilla et al. (2016). Agri., Ecos. & Envir.

Simulation of N_2O emissions using STICS for 3 Mediterranean sites





Selected treatments	Nitrification N_2O-N ($kg\ N_2O\text{-}N\ ha^{-1}\ yr^{-1}$)	Denitrification N_2O-N ($kg\ N_2O\text{-}N\ ha^{-1}\ yr^{-1}$) (1)	Tota[l] ($kg\ N_2$[…]	
HWD	0.08 (0.05) c	0.19 (0.14) c	0.26 (0.16) c	0.69 (0.15) b
MWD	0.27 (0.14) b	0.38 (0.31) b	0.65 (0.43) b	0.56 (0.11) c
LWD	0.58 (0.18) a	1.92 (0.80) a	2.51 (0.90) a	0.75 (0.09) a
Cer rot.	0.32 (0.25) a	0.82 (0.90)	1.13 (1.12)	0.67 (0.14)
CerLeg rot.	0.30 (0.24) b	0.84 (0.95)	1.15 (1.16)	0.67 (0.14)

Plaza-Bonilla et al. (2016). Agri., Ecos. & Envir.

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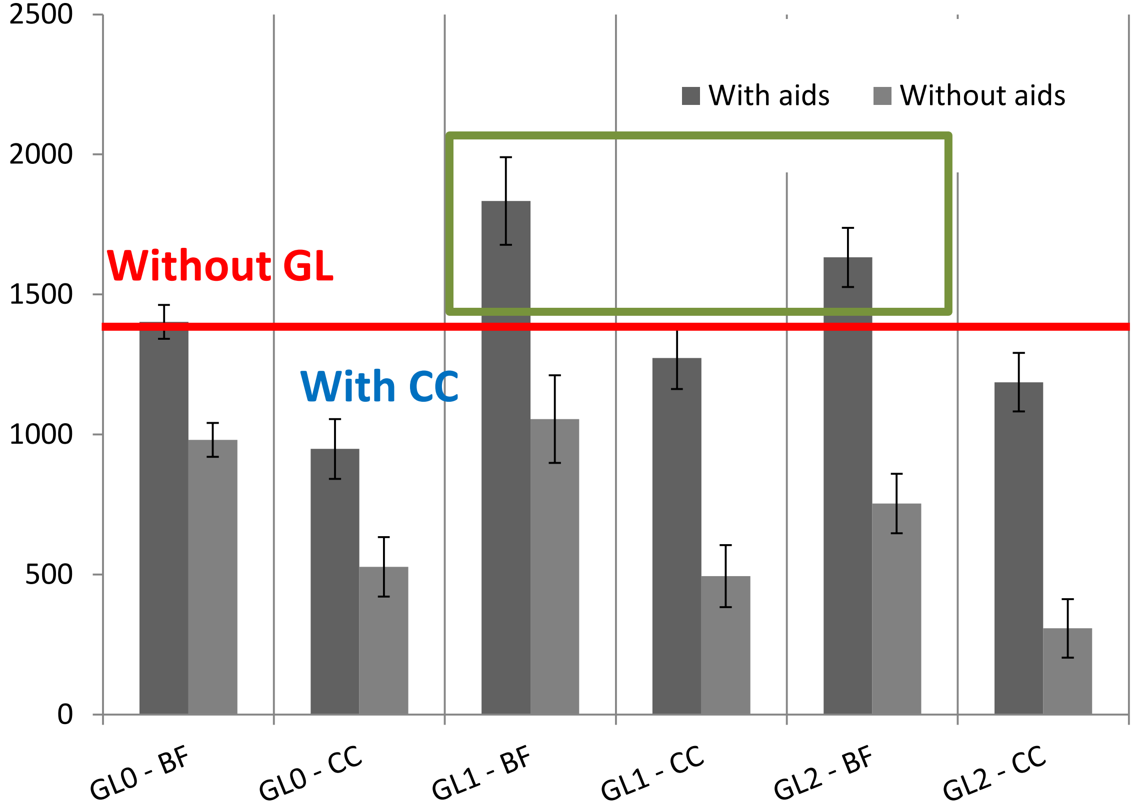
4) **However, Cover Crop insertion in legume-based cropping systems led to:**
   i. **reduced NO_3 leaching (from 15 to 18 kg N ha^{-1})**
   ii. **mitigated SOC loss, and,**
   iii. **did not affect durum wheat grain protein concentration or yield.**
5) **Daily measured N_2O emissions over the whole 3-year rotation were low but significantly higher under the cropping systems including fababean than for the cereal-based cropping system (1.12 vs. 0.78 kg N_2O-N ha^{-1} year^{-1}) despite a lower N fertilization: *fortunately indirect $N_2 0$ emissions are lower!***

What about money? *(from our data)*

3-year rotation semi-net margin with and without aids* (€ ha^{-1} 3 $years^{-1}$)



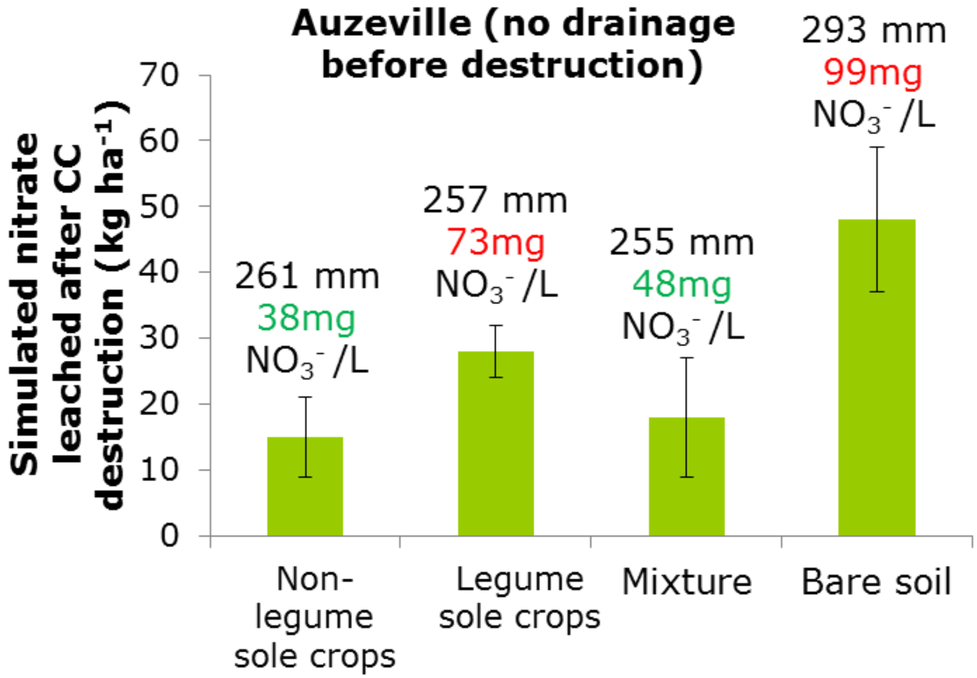
Arable cropping systems <u>including grain legume</u> were more profitable *in our experimental conditions*

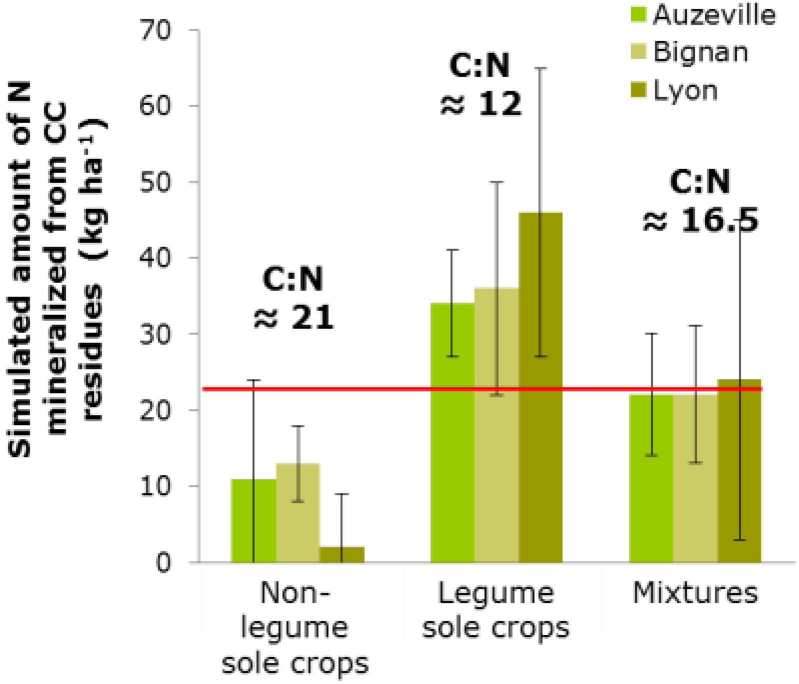
*Aids:
- Basic payment: 132 € ha^{-1}
- Green payment (in GL1 and GL2): 86 € ha^{-1}
- Production-linked payments: durum wheat, pea and soybean (25, 100 and 100 € ha^{-1}).

From Irene Nogué Master's of thesis (2016):
paper in preparation for Agricultural systems

Some other key messages dealing with legume insertion in cropping systems

Cover crops for both nitrate capture and green N manure





Nitrate leaching simulation (destruction after autumn)

- **N leached:**
  Mix.≈Non-leg. SC < Leg. SC
- **[NO3-] in drained water:**
  Mix.≈Non-leg. SC < Leg. SC < BS

N mineralization from CC residues

- **N mineralized from residues:** Non-leg. SC < Mix. < Leg. SC
- **C:N ratio:**
  Leg. SC < Mix. < Non-leg. SC

Tribouillois et al. (2016). Plant and Soil.

Grain legume intercrops to improve productivity and stability by species complementarity

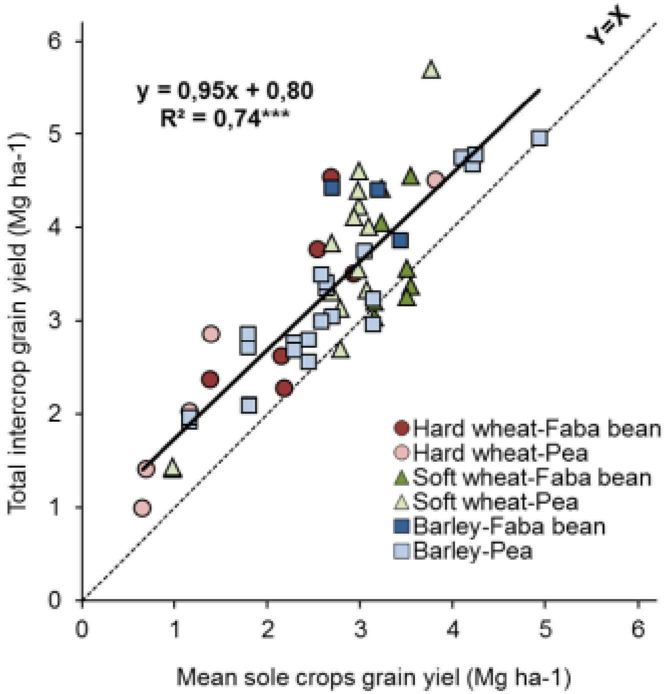
- **10 years of experiments**
- **Various pedoclimatic conditions:** NW, SE, Denmark
- **Conventional and organic farming**
- **Experimental station and farm**
- **Spring and Winter crops**
- **Large range of practices**
  - **Cultivars**
  - **Densities**
  - **Sowing paterns**
  - **Fertilization N or P**
  - **Pest management**

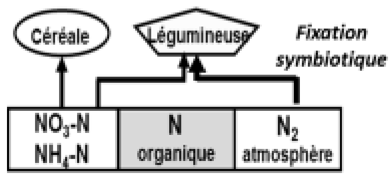
❑ **Different aims :**

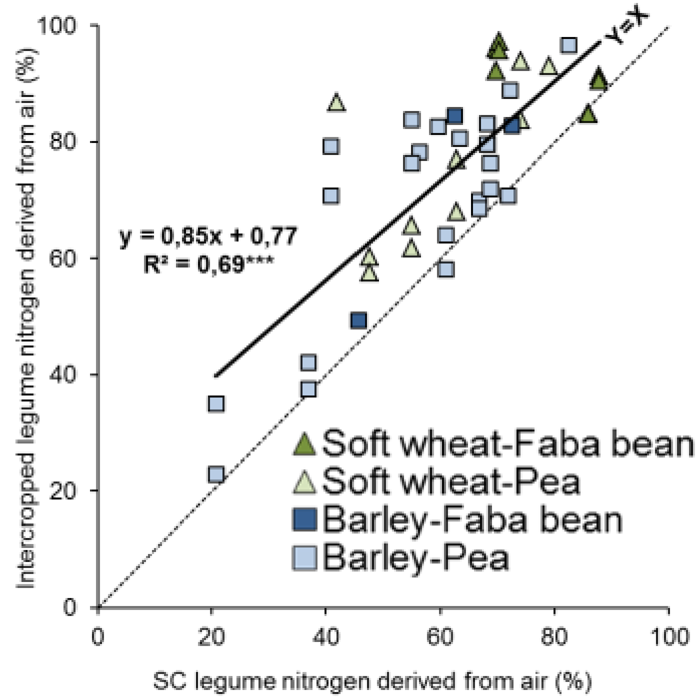
➢ **Evaluate their potential advantages for grain yield, grain protein concentration, weed and pests control**

➢ **Analyze their functioning to further propose optimized intercropped systems**

Intercrops improve yield by species complementarity for N Sources (soil mineral N and N_2 from air)







- Intercrop yield higher than the mean sole crops (3.3 vs 2.7 Mg ha-1)
  - Highest efficiency for low N
- Intercrop grain yield more stable
  - Higher resiliency
- Proportion of cereal > 50%
  - Cereal more competitive

- Higher legume N2 fixation rate in intercrop (75% vs. 62%)
  - Niche complementarity for N sources & competition for soil N
  - Most of soil N mineral available for the cereal
  - Intercrop efficiency higher in low N

Bedoussac et al. (2015). Agron. Sust. Dev.

Grain legume intercrops to improve productivity and stability by species complementarity

- ✓ Intercropping is an efficient way to improve yield and grain quality
  - ➢ Competition for similar resources (in time, space or chemical form) are limited
  - ➢ Facilitation process occurred (e.g. P) or niche complementarity (e.g. N)
- ✓ Intercropping advantages mostly occurred in limited abiotic resource conditions (low inputs or organic farming); various papers of Jensen *et al*., Hauggaard-Nielsen *et al*., Corre-Hellou *et al*., Bedoussac & Justes)
- ✓ N transfers between species are limited for annual crops (in range of error)

- ✓ The best mixtures depend on various levers: species, cultivars, fertilization…
- ✓ **Modelling intercropping systems could be helpful to optimize them and to determine species and varietal characteristics suited to mixtures**





Conclusions

- Then, considering the 5 main results, in such conventionally-tilled systems, **properly designed cropping systems need to simultaneously insert grain legumes and cover crops -including legumes-** in order to reduce NO_3 leaching, stabilize SOC/SON contents without modifying N_2O emissions in field at the rotation level → **efficient N recycling system**

- The STICS model shows a good ability to simulate different soil and crop processes under the pedoclimatic conditions of the experiment: **a relevant tool for doing a more quantitative multicriteria analysis**

- **Mixtures of species of legume and non-legume is an efficient way** to increase grain production (intercrops) in low input & organic systems

- **For providing various ecosystem services**, cover crops need to be compose as a mixture of legume and non-legume species (gramineous, crucifereous) to simultaneously trap nitrate AND provide green N manure effect (multi-services), AND ALSO bio-fumigation effect for bio-control of weeds and soil-borne pathogens (cruciferous): **an approach insufficiently explored!**

Towards innovative sustainable cropping systems

- ✓ **Then our challenge is to RE-DESIGN arable cropping systems with more legumes for providing multi ecosystem services as a way of “strong agroecology”: YES WE CAN!**
- ✓ This paradigm of agroecology to re-redesign must to be considered at the **territorial scale** (see key-note M.H. Jeuffroy) and at the **whole agro-food chain**
  → **Need to UNLOCK the system!** (see talk M-B. Magrini)
- ✓ **Legumes** offer a solution to **attenuate climate change** (tested in Climate-CAFE)
- ✓ A number of factors still **needs to be optimized** before obtaining the full potential of intercropping, in particular to control pests and diseases
- ✓ The **optimum rotational position of intercrops or the analysis of the potential resilience to climate change** need to be analyzed for proposing relevant solutions… Modelling is a RELEVANT TOOL for exploration

AGIR and VASCO Web sites: http://www6.toulouse.inra.fr/agir
Research_Gate personal Web page: https://www.researchgate.net/profile/Eric_Justes
MicMac-Design web site: http://www6.inra.fr/micmac-design
Climate-CAFE EU projet: http://www6.inra.fr/climate-cafe

Thank you for your attention

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