Environmental and economic performances of catch crops between green pea and winter wheat

Catch crops trial. *Credits: Greenotec*

MSc Thesis Double Degree Organic Agriculture-Agroecology

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Abstract

Green pea-winter wheat succession is common in northern France and Wallonia (Belgium) and is known to cause high levels of nitrate leaching. Catch crops have been proven to effectively reduce nitrate leaching in other contexts. However their impact on nitrate leaching and on the subsequent yield varied depending on the catch crop species used. Walloon government enforces their farmers to grow catch crops between green pea and winter wheat since 2014. Our study aimed at studying the effect of different catch crop species composition as well as bare fallow on the nitrate leaching following green pea harvest. We also looked at the yield of the following winter wheat and the corresponding farmers' gross margin. The data of a five years on-farm experiment was analyzed with the support of a mixed effect linear model. It was completed with a cost-benefit analysis based on the experimental results and with soil mineral N dynamic simulations using the model NDICEA. Based on the data available, we defined three indicators: a nitrate leaching indicator, a mineral nitrogen uptake by catch crops indicator and a nitrate uptake indicator. Catch crops reduced nitrate levels before the leaching period below the legal threshold and reduced the nitrate leaching indicator by more than 50% compared to bare soil. Pure non-legumes catch crops were the most effective, reducing the nitrate leaching indicator by 72% in average. All CC led to lower winter wheat yields compared to bare soil (between 0.1 and 0.7t/ha) except the pure legumes mix that had a positive effect in average (+0.2t/ha) but insignificant. All CC resulted in a gross margin reduction compared to bare soil ranging from a 2% to a 10% loss. The yield differences could be partly explained by a N

immobilization effect and partly by limited winter wheat emergence due to reduced seed bed quality when sowing in destructed Catch Crops.

Keywords

Catch crop, nitrate leaching, green pea, winter wheat, gross margin, Wallonia

Abbreviations

B=Buckwheat
Biomax=White Mustard+Lacy Phacelia+Niger+Sunflower+Common Vetch
CC=Catch crops
CCE=Catch crop experiment
CCFE=Catch crop and fertilization experiment
CoV_PV_EC=Common Vetch+Purple Vetch+Egyptian Clover
Leg=pure leguminous CC
LO_EC=Lopsided Oat+Egyptian Clover
Mix=leguminous and non-leguminous CC mix
Ni=Niger
non-Leg=pure non-leguminous CC
O_V=Oat+Vetch
RCBD=Random Complete Block Design
RQ=Research question
WM=White Mustard
WM_P=White Mustard+Phacelia
WO=White Oat
WO_CoV=White Oat+Common Vetch
WO_ChV_F=White Oat+Chickling Vetch+Fenugreek
WW=Winter Wheat

1. Introduction

The agricultural practices that emerged from the Green Revolution are today responsible for numerous environmental disservices around the world (Henneron et al., 2015; Postma-Blaauw et al., 2010), such as soil fertility loss (Sainju et al., 2003; Tilman et al., 2002) and pollution of surface and groundwater with nitrate and pesticides (Constantin et al., 2010; Sainju et al., 2003; Tilman et al., 2002). They form the system of practices that we call today "Intensive agriculture", among which we find ploughing, soil not covered after main crop harvest and high mineral fertilizer input. These practices relies on high levels of external input which ultimately goes along with high costs for farmers (Hoyt and Mikkelsen, 1991). In this context, pea cultivation (*Pisum sativum*) harvested at immature stage (green pea) has been shown to result in 100 to 120kgN-NO3/ha leaching, 50-60kgN-NO3/ha higher than for after a cereal crop or a dry pea crop (Thomsen et al., 2001). This result in a loss of potential fertility for the subsequent cash crop (Plaza-Bonilla et al., 2017) and an environmental pollution.

Catch crops (CC) are crops grown during the fallow (or intercrop) period specifically for ‘trapping’ residual soil nitrate in their biomass and to prevent nitrate leaching. Catch crop cultivation during long intercrop periods has been shown to reduce effectively autumn and winter nitrate leaching (Justes et al., 2012). The nitrate absorbed in the CC’s biomass is partly released for the following cash crop providing nitrogen (N) fertilization without additional cost (Jensen, 1992). The fallow (or intercrop) period refers to the time between the harvest of the main crop and the sowing of the next one. After a main crop harvested in summer, an intercrop period is "long" when the following main crop is a spring crop (i.e. sown in spring or late winter) or "short" when it is a winter crop (i.e. sown in autumn). Short intercrop periods often present low nitrate leaching risk and don't give sufficient time to grow a CC. Therefore, CC cultivation in this context has been little studied. Green peas are harvested beginning of summer in northern Europe, leaving time for a CC to develop. Therefore, CC are of interest in short intercrop period following a green pea.

The effectiveness of catch crops in reducing N leaching depends on the catch crop species, soil, climate and cropping system (Aronsson et al., 2016; Justes et al., 2012). Leguminous CC are attractive for farmers to grow as they fix nitrogen and release it after destruction for the subsequent crop (Valantin-Morison et al., 2014). However, pure leguminous catch crops have a moderate effect (Justes et al., 2012; Toffoli et al., 2012) or a negative effect (Aronsson et al., 2016) on N leaching reduction. Mixed legume-non legume catch crops are more effective and may be as effective as a pure non-leguminous cover crop in reducing soil nitrate content and nitrate leaching (Aronsson et al., 2016; Justes et al., 2012; Toffoli et al., 2010). However, their relatively high C:N ratio compared to the C:N ratio of the soil biota may result in immobilization of soil N in soil biota biomass, making it not available for the following main crop (Justes et al., 2012). Consequently, the choice of CC entails striking a balance between best environment protection and highest economic benefits. Therefore, there is a need for research on the CC choices giving the best compromise in various soil, climate and market conditions.

In Wallonia, pea cultivation for freezing and canning represents around 5 800 ha, which is equivalent to 44% of open field vegetable production (Direction de l'Analyse économique Agricole). Pea is agronomically recognized as a very good precedent crop for winter wheat, increasing wheat yield while decreasing its need for N fertilization (Labreuche, 2013; Plaza-Bonilla et al., 2017). Walloon farmers cultivating green pea commonly grow winter wheat (WW) as the following main crop (pers. com. Greenotec 28/02/2017, 13/06/2017).

In June 2014, as part of the implementation of the European Nitrate Directive that aims to prevent nitrate pollution by agricultural sources (European Commission, 1991), the Walloon government issued a regulation on the management of green pea-WW succession. Farms in so-called nitrate-vulnerable zones have to grow a CC between a green pea crop harvested before the 1st of August and a winter wheat crop. Additionally, the share of leguminous seed in the CC mix was limited to a maximum of 50 % on a weight basis (Nitrawal asbl, 2017). Following the advice of Nitrawal, the research group for N pollution issues in Wallonia, this limit replaced the previous ban of legumes in the CC between green pea and WW (Toffoli et al., 2012). Land in nitrate-vulnerable zones represents virtually all the Walloon cereal and vegetable production area. Therefore most of the farms cultivating a succession green pea – WW are affected by this law (Nitrawal asbl, 2017). It makes green pea-WW succession in Wallonia a relevant case study for CC management in a short intercrop period following a grain legume.

Very few studies have been done on the impact of different CC compositions on N leaching risk, WW performance and farmer gross margin for a short fallow period following a green pea crop, especially in the Walloon conditions. Applied research on conservation agriculture practices is the core activity of an active group of farmers in Wallonia. They founded the research group Greenotec in 2006. The group has a membership of 247 (2016), among which a majority is farmers. The 2016 Conservation Agriculture Fair they organized hosted 800 farmers and numerous companies, associations and administrative bodies involved in conservation agriculture development in Wallonia (Greenotec, 2016). Anticipating the regulation on green pea-WW intercropping, Greenotec and Nitrawal together launched an experiment in 2012 to evaluate economic and environmental consequences of different CC management techniques. The data of the experiment have so far not been analyzed as a whole. Greenotec therefore commissioned the study reported here in order to provide answers to farmers and government. Data analysis with the help of statistical approach adapted to cross-year analysis was performed. It was completed by a modeling of N dynamics for different soil cover types with the NDICEA, to get further insight on the mechanisms responsible for the experimental results obtained.

This study aims at assessing the environmental and economic consequences of various CC. Two research questions have been developed to meet that goal:

(i) What are the relative effects of different catch crop species and bare soil intercrop on winter nitrate leaching?
(ii) What are the relative effects of different catch crop compositions and bare soil intercrop on winter wheat crop in terms of wheat yield and gross margin?

CC are expected to decrease nitrate leaching compared to bare soil (Constantin et al., 2010; Justes et al., 2012). Pure non-leguminous CC (non-Leg) (Justes et al., 2012) and mixtures of legumes and non-legumes species CC (Mix) (Aronsson et al., 2016; Toffoli et al., 2010) are foreseen to best reduce it. Pure legumes CC (Leg) are expected to reduce nitrate leaching less well (Aronsson et al., 2016; Justes et al., 2012). From the highest to the lowest, WW after Leg is conjectured to give the highest yield, then WW after Mix, and the lowest yield is expected for non-Leg. Plots with a bare fallow period are thought to give similar yield than Mix (Justes et al., 2012; Thorup-Kristensen et al., 2003)

2. Materials and methods

2.1. Experiments

This study uses the results of two successive field experiments located on the fields of the farmer Benoît Vandevoorde in the village Sart-Messire-Guillaume (Belgium) within an area of 4.5km². The experiments started each year at CC sowing and ended at WW harvest (see Figure 1). The first experiment tested the influence of different CC composition on soil mineral nitrogen dynamics and WW yield. This experiment, referred to as "catch crop experiment" (CCE), was carried out during three cropping seasons from 2012 to 2015. The second experiment resulted in the addition of the fertilization factor to the first experiment during 2015-2017 cropping seasons. It is referred as "catch crop and fertilization experiment" (CCFE). The WW was not yet harvested in 2017 at the time this study was conducted.

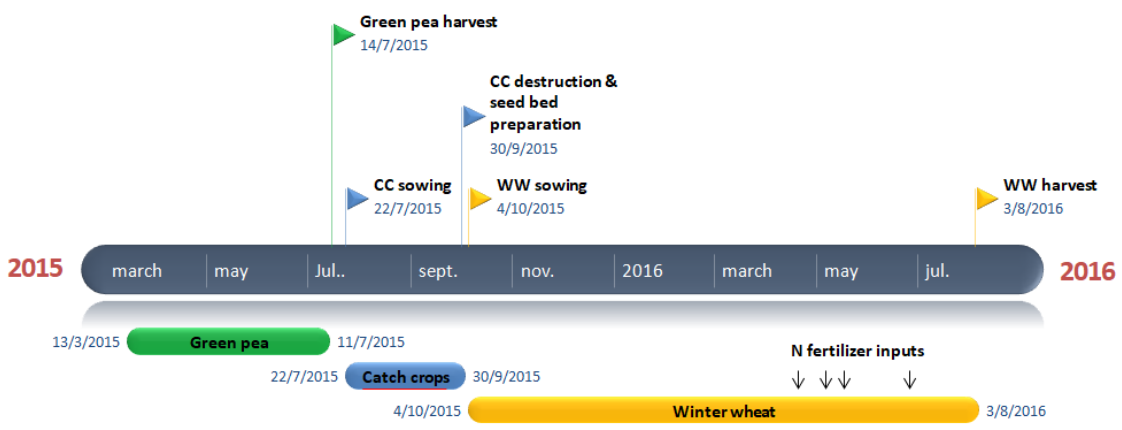

Figure 1 – Timeline of field operations in green pea-winter wheat succession for a typical cropping season.

The experiments changed field every cropping season following the farmer's crop allocation pattern and resulting in five experimental sites (Figure 2). The fields' cropping history was slightly different but all followed a comparable rotation: linseed – beetroots – winter wheat – green pea – winter wheat. All the fields had been under reduced tillage management since 1987 and none had been ploughed since 2003. All fields were similar in elevation, texture and fertility (Table 1 and Appendix 1).

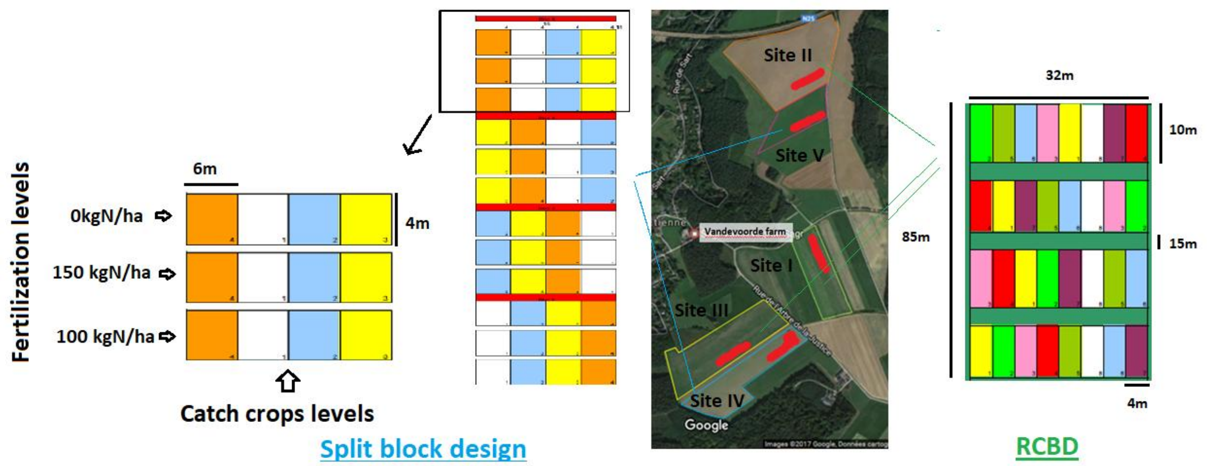

Figure 2- Experimental site and design. The colors in the design represent different soil cover types. The red surfaces on the sites represent the location of the experiment.

For CCE and CCFE, catch crop and winter wheat were both sown with a disc seed drill combined with an integrated power harrow. The seedbed for the CC was prepared with a stubble tine harrow Lemken Smaragd. The CC was destroyed with a flail mower Omarv TTF and the seedbed for the WW was prepared with a cultisoc. Wheat sowing density was 140kg/ha. All other cultivation practices (e.g. pesticide spraying) were adapted to each year's condition. A summary of the cultivation practices can be found in Appendix 2. Catch crops species tested changed across trials and across years for the same trial (Table 2). They were gathered under 3 categories: pure legumes (Leg), mixture of legumes and non-legumes (Mix) and pure non-legumes (non-Leg). This categorization allowed identifying the effects of the proportion of legume species in the mix on the response variables. A bare soil (or no-CC) treatment was always used as a control. These bare soil plots (bs) represent the fourth "soil cover category". Each year, 160 to 167kgN/ha was applied on the wheat in 3 to 4 different applications from end of February to beginning of June. Liquid urea ammonium-nitrate was used as N fertilizer for CCE and solid ammonium-nitrate for CCFE. Three different levels of N fertilization were applied in the CCFE: 0, 100 and 150 kgN/ha (control). The WW was harvested with an experimental harvester.

Table 1 – Experiment site and design description

Cropping season	**2012-2013**	**2013-2014**	**2014-2015**	**2015-2016**	**2016-2017**
Experiments	CCE			CCFE	
Location	Sart-Messire-Guillaume (Belgium)				
Localization [1]	Site I: 50°37'10.0"N 4°34'30.3"E	Site II: 50°37'41.5"N 4°34'26.8"E	Site III: 50°36'48.8"N 4°33'59.2"E	Site IV: 50°36'53.2"N 4°34'21.5"E	Site V: 50°37'35.0"N 4°34'26.5"E
Altitude [2]	133-138	120	143	140-143	125
Plot size (m²)	40	40	40	24	24
Soil [3]					
- **texture [4]**	Silt loam	Silt loam	Silt loam	Silt loam	Silt loam
- **pH [5]**	6.3	6.1	*NA*	6.7	6.3
- **humus content [6]**	2.3%	2.0%	*NA*	2.9%	2.4%
- **nutrient status [7]**	Good	Good	*NA*	Good	Good
Wheat cultivars	Edgar	Edgar	Napolice	Edgar	RAGT Réforme
WW sowing density (kg/ha)	140	155	140	140	*NA*
N fertilization (kgN/ha)	160	167	164	150	
Type of design	RCDB			Split block (or strip plot)	
Nb of blocks	4				
Factors (nb of levels)	CC (5)	CC (10)		CC (4) Fertilization (3)	
Mean temperature [8]	9.4°C	11.0°C	10.7°C	10.9 °C	*NA*
Annual precipitation (mm) [8]	607.7	655	687.9	873.8	*NA*

RCBD=Random Complete Block Design, CC=Cover crop, F=Fertilization, DST=CC Destruction and WW Sowing Techniques, *NA*=no data available. Meteorological data calculated on a cropping season (from 8th of August to 7th of August next year).[1] See map in Figure 2, [2] See topographic map in Appendix 1, [3] See pedological map in Appendix 1, [4] According to USDA soil texture reference (n.d.), [5] pH measured in a solution of 1N KCL according with the norm NF ISO 10390, [6] Organic carbon*2, calculated according to Pribyl (2010), [7] The nutrient status is defined according to the reference values from the "Commission des Sols de Wallonie" determined by A. Descamps (unpublished), [8] data retrieved by ASBL Pameseb from the Baisy-Thy.

Table 2 - Catch crops tested from 2012 to 2017 on sites I to V

Year	2012-2013	2013-2015	2015-2017
Site	I	II&III	IV&V
Experiment	CCE		CCFE
Catch crops	White mustard (*Sinapis alba*)	White mustard	White mustard + Lacy phacelia
	Niger (*Guizotia abyssinica*)	White mustard + Lacy phacelia (*Sinapis alba + Phacelia tanacetifolia*)	White oat + Common spring Vetch [2]
	Buckwheat (*Fagopyrum esculentum*)	Niger	Lopsided oat + Egyptian clover
	White Oat (*Avena sativa*)	White oat	Bare soil
	Buckwheat+Egyptian clover (*Fagopyrum esculentum+ Trifolium alexandrium*)	Buckwheat	[3]
	Bare soil	Oat[1]+Purple vetch (*Avena sp. + Vicia benghalensis*) [2]	
		Lopsided oat + Egyptian clover (*Avena strigosa +Trifolium alexandrium*)	
		White oat+Chickling vetch +Fenugreek (*Avena sativa +Lathyrus sativus + Trigonella foenum-graecum*)	
		Common vetch (*Avena sativa*) + Purple vetch + Egyptian clover	
		Bare soil	

Orange=Pure non- legumes (non-Leg), green=mix legumes and non-legumes (Mix), blue=pure legumes (Leg=, grey=control (bs). The sowing rates of the cover crop mixtures can be found in Appendix 2. [1] 2013-2014: White oat, 2014-2015: Lopsided oat ; [2] For the cross year analysis, all the CC mix Oat+Vetch will be considered as one factor level. [3] A biomax CC was tested on a similar trial placed on the same field and will be included in the analysis. It is composed of legumes and non-legumes species: Common Vetch +White Mustard+Lacy Phacelia+Niger+Sunflower

CCE trials were following a random complete block design (RCBD). CCFE trials were following a split block or split plot design (Figure 2). Data from the CCFE with fertilization level of 150kgN/ha (optimal fertilization level) were gathered with data from CCE for the 5-years analysis. They can be considered as coming from a random complete block design as well as the split block design with only one factor is a similar to a RCBD.

2.2. Data collection

Four types of data were collected: (i) soil mineral nitrogen content on the 0-90cm layer at 4 different times, (ii) CC biomass, (iii) WW plant density (in 2015 only) and (iv) WW yield.

Soil mineral nitrogen content was measured on composite soil samples of the first 90cm taken from each plot. After being collected, each composite sample was mixed and sieved. A subsample was taken. Nitrate and ammonium were extracted with a 0.5N KCl solution. The solution was kept at 4-5°C, then sent to the laboratory Michamps for nitrate and ammonium dosage (certification: NBN EN ISO/IEC 17025:2005 and EN ISO 14001:2004). The analyses were done 4 times per season: (i) at the beginning of August just before CC sowing, (ii) at the beginning of October just after CC destruction, (iii) at mid-December when the N leaching period starts and (iv) at the beginning of March when the N leaching period ends and the vegetative period restarts.

CC biomass was harvested on at least 4 m² either manually (2012-2014), with a Haldrup™ harvester (2014-2016) or with a flail mower (2016-2017). The fresh biomass was weighted and a sample was dried in the oven for 2 days at 90°C to determine biomass dry matter per hectare.

Wheat plant density was determined in autumn 2014, 24 days after sowing (wheat with 2 to 3 leaves) on a 0.25m² square randomly chosen in each plot, with two repetitions per plot. Wheat plant density was not determined for the other cropping seasons.

Wheat was harvested on a 1 to 1.5m wide strip at the center and across the length of the plots with an experimental harvester (Redebel). The grains harvested were weighted automatically and divided by the surface harvested to obtain the yield.

Meteorological data were collected by the association Pameseb. Mean, maximum and minimum temperature, rainfall and reference evapotranspiration data were retrieved daily from the meteorological station of Baisy-Thy.

Measurement numbers per treatment varied across and within years depending on the data collected. A summarizing table can be found in Appendix 3.

2.3. Experiment results analysis

2.3.1. Reference for October-December soil nitrate content

In Wallonia, farmers have an obligation of result concerning the level of soil nitrate content in their field just before the leaching period (October-December). Based on a reference of group of 36 to 42 Walloon farms recognized for their good nitrate management, the Walloon authorities and their scientific partner defined four categories of soil nitrate content for October and December: (i) "Good" levels below the median of the reference groups level, (ii) "Satisfactory" levels between the median and the 66th percentile (75th in 2012), (iii) "Pass" levels between the 66th percentile (75th in 2012) and the intervention threshold, (iv) "Bad" levels higher than the intervention threshold. The intervention threshold is based on the 66th percentile (75th in 2012) plus a measurement error margin based on the median value (GRENeRA and U. C.L. 2016, 2015, 2014, 2013, 2012). It is illegal for farmers to have a soil nitrate content in their field higher than the intervention threshold. The thresholds defining those categories are updated every year based on new measurements in the reference farms. The intervention threshold of soil nitrate range from 81 to 128kgN-NO3/ha in October and 88 to 121kgN-NO3 in December. The aimed level ranged from 36 to 63 kgN-NO3 in October and 57 to 89kgN-NO3/ha in December. See Appendix 4, for the complete set of references. In our study, each CC treatment has been evaluated every year for its average soil nitrate content, both in October and December with regard to the legal reference.

2.3.2. Mineral nitrogen dynamic indicators

Based on the data collected, the following indicators were calculated: (i) indicator of the total amount of mineral nitrogen (ammonium+nitrate) taken up by the different CC ($Nmin_{upt}$) in kgN/ha, (ii) indicator of the total amount of nitrate taken up by the different CC ($NO3_{upt}$) and (iii) indicator of the total amount of nitrate leaching ($NO3_{leached}$) in kgN-NO3/ha.

(i) $$Nmin_{upt} = (Nmin_1^{cc} - Nmin_2^{cc}) - \left(Nmin_1^{bs} - Nmin_2^{bs}\right)$$

$Nmin_{upt} = Nmin_{Oct}^{bs} - Nmin_{Oct}^{cc}$ as $Nmin_1^{cc} = Nmin_1^{bs}$

$Nmin_t^{cc}$ is the measured soil mineral nitrogen content just before CC sowing (t=1) and just after CC destruction (t=2), and $Nmin_t^{bs}$ is the measured soil mineral nitrogen content in bare soil at the same times t=1 and t=2. We make the hypothesis that compared to bare soil control, CC only differ significantly regarding the soil mineral nitrogen balance by modifying mineral nitrogen uptake by plants.

(ii) $$NO3_{upt} = NO3_2^{bs} - NO3_2^{cc}$$

The notations are the same than for total mineral nitrogen uptake.

(iii) $$NO3_{leached} = (NO3_3^{cc/bs} - NO3_4^{cc/bs})$$

$NO3_3$ and $NO3_4$ are respectively the amounts of soil nitrate pre-leaching period (in December in our trials) and post-leaching period. COMIFER (French Committee of Research and Development on Sustainable Fertilization) stated that the amount of nitrogen denitrified during the leaching period could be neglected (Cattin et al., 2002). We assumed that the result of the nitrate mineralization, uptake and immobilization due to the bacteria and plant activity during the winter leaching period can be neglected. Therefore, we considered that the difference between the soil nitrate levels before and after the winter leaching period corresponded to the amount of nitrate leached.

These indicators are represented in Figure 3.

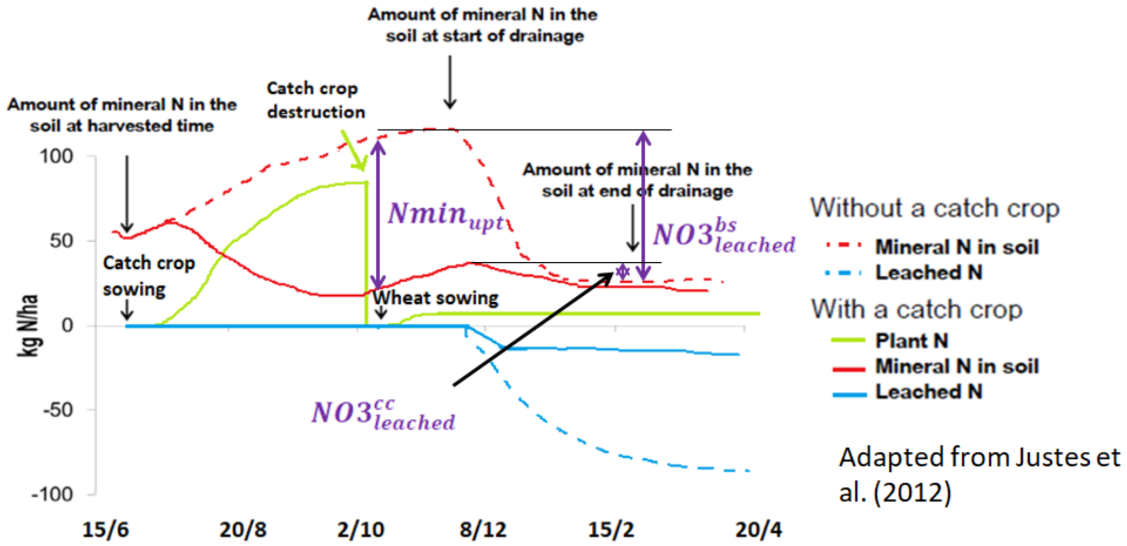

Figure 3- Expected mineral nitrogen dynamic and corresponding indicators. Ammonium being not prone to leaching is $NO3_{leached}$ considered equal to $Nmin_{leached}$. $NO3_{upt}$ would be represented the same way than $NO3_{upt}$ if the curve were representing nitrate dynamics. Nitrate dynamics and mineral nitrogen dynamics are expected to be similar.

2.3.3. Statistical analysis

The experimental data of the CCE experiment were combined with CCFE data from the plots fertilized with 150kgN/ha (control fertilization level) .The data from CC not tested at least 2 years were removed. The resulting dataset was used to analyze the effect of CC species composition on response variables. The five sites and years used were characterized by small differences in observed soil characteristics and rotations, and contrasting meteorological conditions and management (Table 2). In order to analyze the data without the year-site effect, a linear mixed model was used (Ott and Longnecker, 2010) using the "lme4" package v1.1-13 (Bates, 2017) with catch crop composition as a fixed factor and year as a random factor. The blocks were considered as simple replications. The following model equation was used in R version v3.4.1 (R Core Team, 2017).

(iv) $lmer(Y \sim catch\ crop + (1|year))$

The normality and homoscedasticity of the residues were checked with a QQ-plot of the residues and a scatter plot of the residues against the fitted values, respectively. Pairwise comparisons were performed with Tukey's HSD test. A log transformation was applied to the dependant variable when the model residues could not be assumed to be normally distributed or homoscedastic. If even after log transformation the model residues could not be assumed to be normally distributed or homoscedastic, Aligned Rank Transform for nonparametric factorial ANOVAs (Wobbrock et al., 2011) was used based on the ARTOOL package v0.10.4 (Kay and Wobbrock J.O, 2016). As in Vrignon-Brenas et al. (2016), homogenous groups were then determined with the per-term linear model from aligned rank transformed data (p = 0.05) using the LSMEANS package v2.26-3 (Russel, 2017). The coefficients given by this model could not be given a natural meaning.

The experimental data of CCFE was analyzed with a split block ANOVA model (O'Neill and J. Lee, 2009) using the Agricolae package v1.2-4 (Menburu, 2016). A Tukey's HSD test was then used for pairwise comparisons in case of significant influence of the factors.

2.4. Mineral N dynamic simulations

NDICEA is a process based model which calculates the soil dynamics of water, carbon, organic matter, organic and mineral nitrogen in top and sub-soil with a 1-day time step of integration. Topsoil represents the layer in which the organic matter is incorporated with tillage and subsoil the rest of the soil still colonized by roots. NDICEA takes as input meteorological data (mean temperature, rainfall, reference evapotranspiration), the soil properties (texture, pH, soil organic matter), the crop succession, the fertilizer applications, tillage regime and the target yield. The outputs we were interested are: dynamics of mineral nitrogen amount in top and sub-soil, available nitrogen, nitrogen crop need, nitrogen leaching and denitrified nitrogen (van der Burgt et al., 2006). The model was developed to be used by extension agents who wish to reconstruct the nitrogen dynamics in cropping systems experiments for a better understanding of the underlying mechanisms (van der Burgt et al., 2006), which fits exactly the framework of this study.

Considering the precision of the model and the choices available in the model, we only represented the three CC categories used in the experiments and bare soil. Each of the three CC category was represented by one typical CC. The categories and the corresponding representation can be found in Table 3.

Table 3- CC mix categories representation in NDICEA model

Categories	NDICEA CC mixes
Legumes-non legumes mix	Oat/Vetch
Pure non legumes	Lopsided oat
Pure legumes	Vetch
Bare soil	No CC

The only cropping season when the mineral nitrogen data was available for the subsoil, the top soil and each of the four soil cover categories was 2013-2014. The model was calibrated manually in collaboration with its co-inventor Gerard Oomen. The four different simulations were run with their corresponding inputs. Only 3 inputs parameters differed from one to another: (i) the average measured biomass of the CC category (except for bare soil), (iv) the average measured WW yield corresponding to the category and (v) the mineral nitrogen levels in the topsoil and subsoil with the corresponding sampling dates. The last input is not used for NDICEA calculations but only plotted on the output as reference.

2.5. Cost-Benefit comparisons

A cost-benefit balance was made for each treatment of the CCE experiment. Only differences between the treatments were accounted for, using the bare soil treatment as reference. Therefore, the costs taken into account were the cost of CC seeds as in the trial, the field operations were all the same. The benefit taken into account was wheat grain revenue.

2.5.1. Costs

Catch crop seed cost was given by the formula below.

(v) $C_X^{CC} = SR_X * P_X$

C_X^{CC} is the seeds cost in €/ha for the catch crop mix "X", SR_X is the sowing rate of mix X in kg/ha and P_X is the 2017 farmer price of mix X in €/kg from the SCAM cooperative (pers. com. SCAM, 10/07/2017).

2.5.2. Benefits

Only the actual benefits the farmers can currently receive were considered. This consists of the wheat grain sales. The premium price for baking quality couldn't be taken into account as the data on wheat grain protein content was only available for 2015. Furthermore, the wheat cultivated was aimed to be fodder wheat and in 2015 the wheat grain protein content didn't reach the required level for baking quality for any of the treatments. Increase in soil quality, nitrate pollution reduction and other environmental services or investment in the natural production capacity of the soil were not economically evaluated. Therefore, the benefits were calculated with the following formula:

(vi) $B^{CC} = (Y_{WW}^{CC} - Y_{WW}^{bs}) * P_{WW}$

B^{CC} is the average benefits of the catch crop "CC" in €/ha, P_{WW} is the average price of the last 3 years of wheat (Belgian federal government, 2017). For the factor CC composition, Y_{WW}^{T} is the average yield corrected by the year effect for treatment "T" (can be any CC or bare soil). It is calculated using the formula (vii).

(vii) $Y_{WW}^{T} = MY + coef_T^{lme}$

MY is the average wheat yield for all years and all treatments and $coef_T^{lme}$ is the coefficient for the treatment, given by the linear mixed model with the model equation (iv).

3. Results

A summary of the statistical analysis results is presented in Table 4, 5 and 6. Details are described in the following sections. All data are available in Appendix 5-10.

Table 4-Level of significance of catch crop categories, catch crops species and nitrogen uptake effects on response variables

Response variables	CC biomass	Nitrate leaching indicator	Yield	WW plant density (2015)	Nitrate uptake indicator	Nitrate level post-leaching period
Model	LME (log transformation)	ARTF	LME	ANOVA	LME	LME (log transformation)
CC categories	**	***	*	ns	*	***
CC species	***	***	*	*	ns	***
CC nitrogen uptake indicator	/	*	*	/	/	/

Significance codes: 'ns' p<0.05, '*' p<0.01, '**' p<0.001, '*** p<0.0001. ARTF=Aligned Rank Transform of Factorial model, LME=Linear Mixed Effect model, '/'=not relevant.

Table 5- Differences of CC categories effect on response variables

Response variables	Control (bs)	non-Leg	Mix	Leg
CC biomass* (tDM/ha)	/ /	**ref** (b)	1.09 (b)	0.62 (a)
Nitrate leaching indicator**	/ (c)	/ (a)	/ (b)	/ (b)
WW yield (t/ha)	**ref** (b)	-0.3 (ab)	-0.6 (a)	0.2 (b)
CC nitrate uptake indicator	/ /	**ref** (b)	-7 (ab)	-31 (a)
Nitrate level post-leaching period*	**ref** (b)	0.57 (a)	0.92 (b)	1.15 (b)

The numbers are coefficients given by the statistical model used. **ref** refers to the reference factor. Similar letters indicate homogeneous group after Tukey's HSD test (α=0.05). non-Leg=pure No Legumes, Mix=Legumes-No Legumes mix, Leg=pure Legumes, '/'=not relevant. The response variables for which the CC categories didn't have significant effect are not represented. * Exponentiated coefficient of LME model with log transformation to be interpreted as the ratio between the geometrical mean of the response variable for the corresponding factor level to the geometrical mean of it for the reference factor level **(ref)**. ** Coefficients are not given due to the Aligned Rank transformation, they cannot be interpreted as such.

Table 6- Differences of CC effect on response variables

	bs	Non-Leg					Mix				Leg
	Control	WM	WM_P	Ni	B	WO	O_V	WO_ChV_F	LO_EC	Biomax	CoV_PV_EC
CC bio-mass*	/ /	**ref** (cd)	1.08 (cd)	0.97 (bcd)	0.88 (abc)	1.02 (bcd)	1 (cd)	1.16 (cd)	0.74 (ab)	1.48 (d)	0.63 (a)
Nitrate leaching indicator**	/ (c)	/ (a)	/ (ab)	/ (a)	/ (ab)	/ (a)	/ (b)	/ (b)	/ (ab)	/ (ab)	/ (b)
WW yield (t/ha)	**ref** (ab)	-0.2 (ab)	-0.1 (ab)	-0.4 (ab)	-0.1 (ab)	-0.7 (a)	-0.7 (a)	-0.5 (ab)	-0.4 (ab)	/ (ab)	0.4 (b)
WW plant density (2015) (nb/m²)	**ref** (a)	-21 (ab)	-33 (ab)	-63 (ab)	2 (a)	/ (a)	-94 (b)	-7 (ab)	-48 (ab)	/ (ab)	-31 (ab)
Nitrate level post-leaching period *	**ref** (d)	0.50 (a)	0.62 (ab)	0.59 (ab)	0.44 (a)	0.69 (abc)	0.91 (cd)	0.9 (bcd)	0.95 (cd)	0.91 (abcd)	1.14 (d)

The upper value is the model coefficient interpretable relatively to the reference factor level (**ref**). The letters below c The response variables for which the CC categories didn't have significant effect are not represented. * Exponentiated coefficient of LME model with log transformation to be interpreted as the ratio between the geometrical mean of the response variable for the corresponding factor level to the geometrical mean of it for the reference factor level **(ref)**. ** Coefficients are not given due to the Aligned Rank transformation, they cannot be interpreted as such. WM=White Mustard, WM_P=White Mustard+Phacelia, Ni=Niger, B=Buckwheat, WO=White Oat, O_V=Oat+Vetch , WO_ChV_F=White Oat+Chickling Vetch+Fenugreek, LO_EC=Lopsided Oat+Egyptian Clover, Biomax=White Mustard+Lacy Phacelia+Niger+Sunflower+Common Vetch, CoV_PV_EC=Common Vetch+Purple Vetch+Egyptian Clover ; non-Leg=pure No Legumes, Mix=Legumes-No Legumes mix, Leg=pure Legumes. "/"=not relevant.

3.1. Catch crops nitrate uptake

The CC nitrate uptake indicator ($NO3_{upt}$) could not be calculated for 2016-2017 because July soil nitrogen sampling was not carry out. The mean indicator for CC nitrate uptake over the four years was 124kgN-NO3/ha. The nitrate uptake indicator of Leg was significantly lower than non-Leg (Table 5) and lower than Mix with p=0.0642. There was no significant difference between non-Leg and Mix, even though Mix CC uptake indicator was in average lower every year (Figure 4).

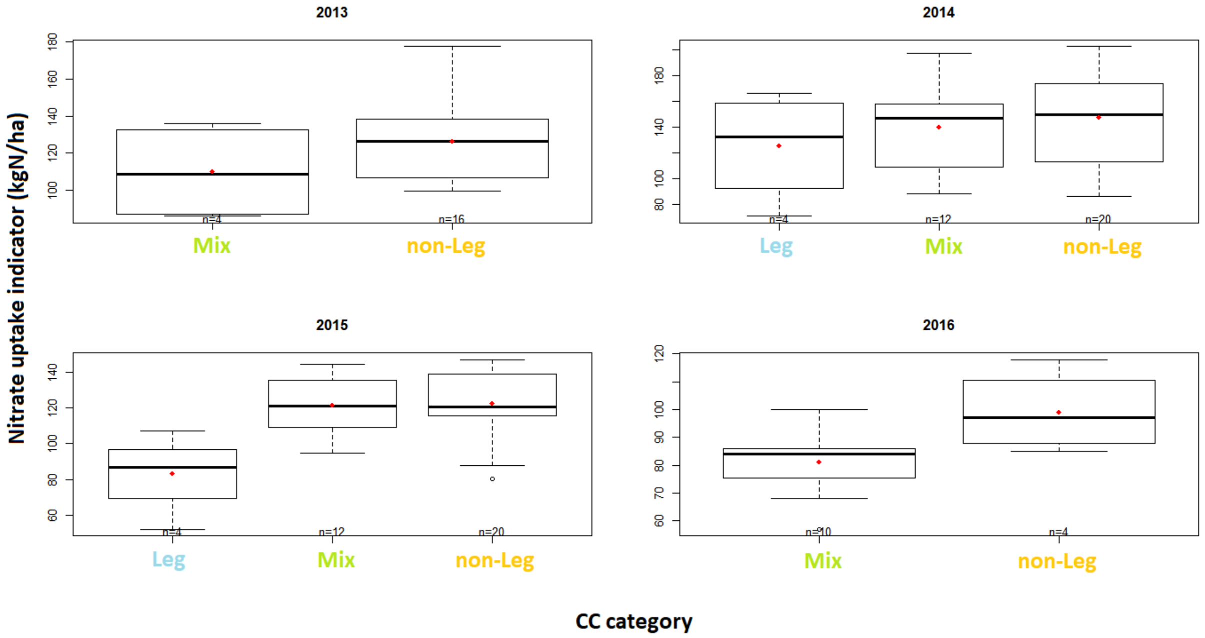

Figure 4- CC nitrate uptake indicator per year and per category. '**.**'= average value; n=the number of individual data point included.

3.2. Catch crop biomass

Average CC biomass on the 5 years experiment was 4.1tDM/ha with a strong heterogeneity across years (2.4tDM/ha in 2015-2016 and 4.8tDM/ha in 2013-2014). There was a strong and significant heterogeneity across CC and across CC categories (Table 6 and 5). Leg biomass was significantly lower than Mix and non-Leg (57% and 62% of their corrected average biomass). With the correction for the year effect, the lowest biomasses were: pure legumes mix, lopsided oat-egyptian clover mix and buckwheat. The highest biomass was found for the biomax mix. You can find the plot of biomass per CC for every year in Appendix 11.

3.3. Autumn nitrate content levels

In October, the average soil nitrate levels were 17kgN-NO3/ha for non-Leg, 23 kgN-NO3/ha for Mix, 49 kgN-NO3/ha for Leg and 137 kgN-NO3/ha for the control compare respectively to 49 kgN-NO3/ha, 68 kgN-NO3/ha, 84kgN-NO3/ha and 135kgN-NO3/ha in December. In October, every year, all CC plots had an average residual soil nitrate level per CC mix considered "Good" but for lopsided oat-egyptian clover in 2015 which got "satisfactory", according with the Walloon legislation references determined by GRENeRA and U. C.L. (2016, 2015, 2014, 2013, 2012) (Appendix 4). Conversely, the bare soil control plots always got a "bad" level which would mean a fine for the farmer. In December, most CC still were at the "Good" level (Table 7). Mix and Leg would be classified as "worse" according to legislation at least half of the years they have been tested, except for white oat-chickling vetch-fenugreek mix. Lopsided oat-egyptian clover reached the "bad" level in 2015. Bare soil control plots average was always at the "bad" level except in 2015 when it was at "pass" level.

Table 7-Evaluation of soil nitrate level in pre-leaching period for CC factor levels

	Good	Satisfactory	Pass	Bad
2012	WM, Ni (others not measured)			Bare soil (control)
2013	All CC but CV_PV_EC and WO_PV		CV_PV_EC and WO_PV	Bare soil (control)
2014	All CC			Bare soil (control)
2015	WM_P, Biomax		LO_CoV, Bare soil (control)	LO_EC
2016	WM_P, Biomax	WO_CV, LO_EC		Bare soil (control)

The evaluation is based on Walloon legislation references obtained by GRENeRA and U. C.L. (2016, 2015, 2014, 2013, 2012). WM=White Mustard, WM_P=White Mustard+Phacelia, Ni=Niger, WO=White Oat, LO_CoV=Oat+Vetch , WO_ChV_F=White Oat+Chickling Vetch+Fenugreek, LO_EC=Lopsided Oat+Egyptian Clover, Biomax=White Mustard+Lacy Phacelia+Niger+Sunflower+Common Vetch, CV_PV_EC=Common Vetch+Purple Vetch+Egyptian Clover

In autumn 2013, in the bare soil plots, a high level of nitrate was measured in the first 30cm in October and found back in the 30-90cm soil layer as well as the nitrate present (Figure 7). There seem to be no significant leaching during this period.

3.4. Nitrate leaching indicator

Across the 5 years, the nitrate leaching indicator was on average 96 kgN-NO3/ha for the control and 34 kgN-NO3/ha for all CC. It was found significantly lower for all CC compared to bare soil (Table 5). On average on the years they were tested, Leg reduced the nitrate leaching indicator by 60%[1], Mix by 58% and non-Leg by 72% compared to bare soil. The nitrate leaching indicator was systematically higher for Mix than for non-Leg (+12kgN-NO3/ha) except in 2013 and the difference was significant (Figure 5). The indicator was slightly higher for Leg than for Mix (+7kgN-NO3/ha). Statistical analysis showed a significant difference between Leg and non-Leg (+14kgN-NO3/ha for Leg) but not between Leg and Mix. However the Mix with 3 species or more had a comparable effectiveness to pure non-legumes (Figure 6). This is particularly the case for the biomax. Conversely buckwheat (B) CC had a nitrate leaching reduction performance very close to Mix CC. The mix CC lopsided oat-egyptian clover had the highest nitrate leaching indicator of Mix and non-Leg CC, but was its indicator was still 51% lower than bare soil.

[1] The data had to be ranked and aligned in order to analyze them statistically. This method doesn't give naturally interpretable coefficient. Therefore, the numbers given here only correspond to averages across the years the treatments compared were tested at the same time. Two of these number can't be compared if the corresponding treatments have not been tested the same year

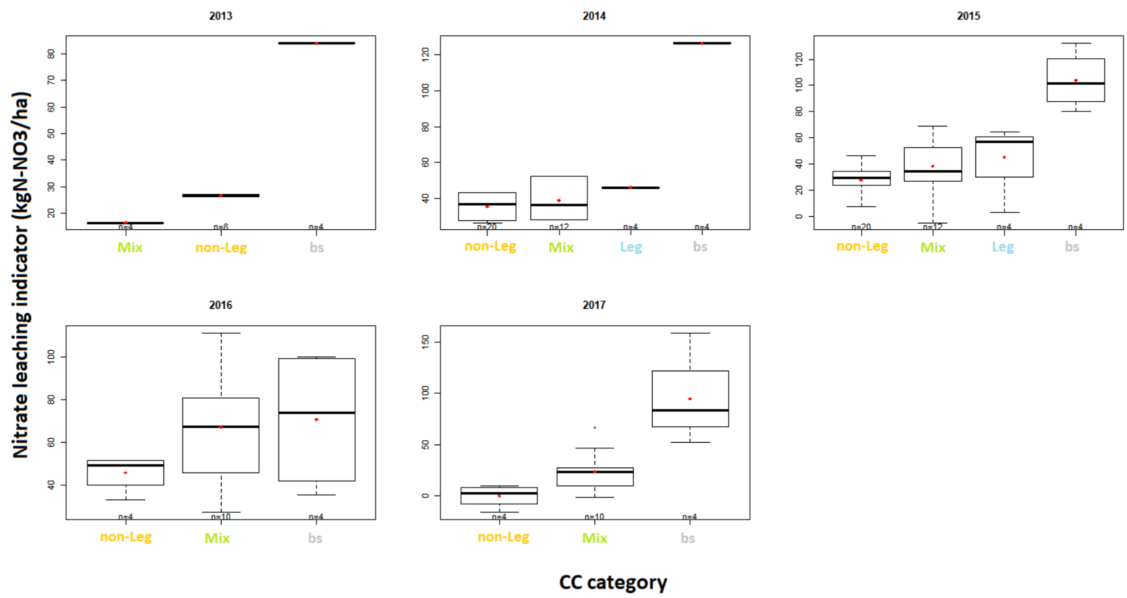

Figure 5- Nitrate leaching indicator per year and per CC category.'.' = average value; n=the number of individual data points included. When there are lines instead of boxes, only one composite sample was taken for soil mineral nitrogen content in December and March this year.

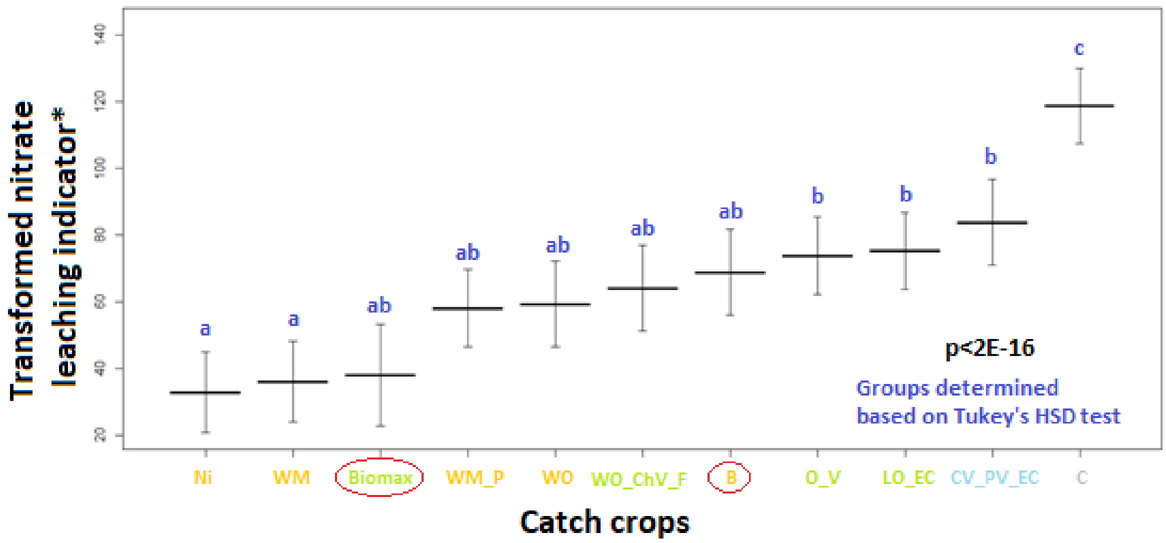

Figure 6- Effect of CC compositions on nitrate loss. *The nitrate leaching indicator data were ranked and aligned in order to realize a nonparametric factorial ANOVA. The groups were determined with the Tukey's HSD test based on the least square means (horizontal lines in the plot) calculated from the model ($\alpha \leq 0.05$). WM=White Mustard, WM_P=White Mustard+Phacelia, Ni=Niger, B=Buckwheat, WO=White Oat, O_V=Oat+Vetch , WO_ChV_F=White Oat+Chickling Vetch+Fenugreek, LO_EC=Lopsided Oat+Egyptian Clover, Biomax=White Mustard+Lacy Phacelia+Niger+Sunflower+Common Vetch, CoV_PV_EC=Common Vetch+Purple Vetch+Egyptian.

3.5. Soil nitrate content post leaching

The mean soil nitrate content post-leaching varied greatly across years from 8kgN-NO3/ha in 2016 to 43kgN-NO3/ha in 2017. In average 39kgN-NO3 were left after control, 38kgN-NO3 after Leg, after 26kgN-NO3 Mix and 21kgN-NO3 after non-Leg. It was systematically and significantly lower for non-Leg than for others (Table 5). No other significant differences were observed between catch crops categories, even though Leg had the highest value the two years it was present (Appendix 12).

3.6. N dynamic simulations

NDICEA calculations underestimated soil mineral N value that were higher than 100kgN/ha (control: -40kgN/ha for topsoil in October, -50kgN/ha for subsoil in December, in average). It overestimated the other soil mineral N level (between +20 and +40kgN/ha for all simulations at all times) except for starting value in July and subsoil in December for CC simulation. The fluctuations over time in mineral N level for CC simulations are not represented neither (Figure 7). However it qualitatively positioned well mineral N level variation in bare soil plots compared to CC plots in autumn. For the period from mid-July (green pea harvest) to mid-October (CC destruction/WW sowing), the soil mineral nitrogen content increased in the topsoil and the subsoil (though too early compared to measurements) for control but decreased for CC in the top and subsoil. For the mid-October to mid-December period, the simulations showed an increase in subsoil mineral N concentration for both control and CC when it showed a decrease for the topsoil concentration in control plots but an increase for the topsoil concentration in CC plots. For the winter period (mid-December to beginning of March), according with the simulations the mineral N concentration slightly decreased in the top and subsoil for the control and stayed stable or increase in CC. Conversely, the measurement showed a strong decrease for the control and a lighter decrease for CC.

Over the all green pea-WW succession, more nitrogen was mineralized with CC than without. Increase in organic N was much higher for CC compared to control (Figure 8). In the simulation, denitrification and WW mineral N uptake (Appendix 13) are not shown to be different between CC and control in NDICEA simulations.

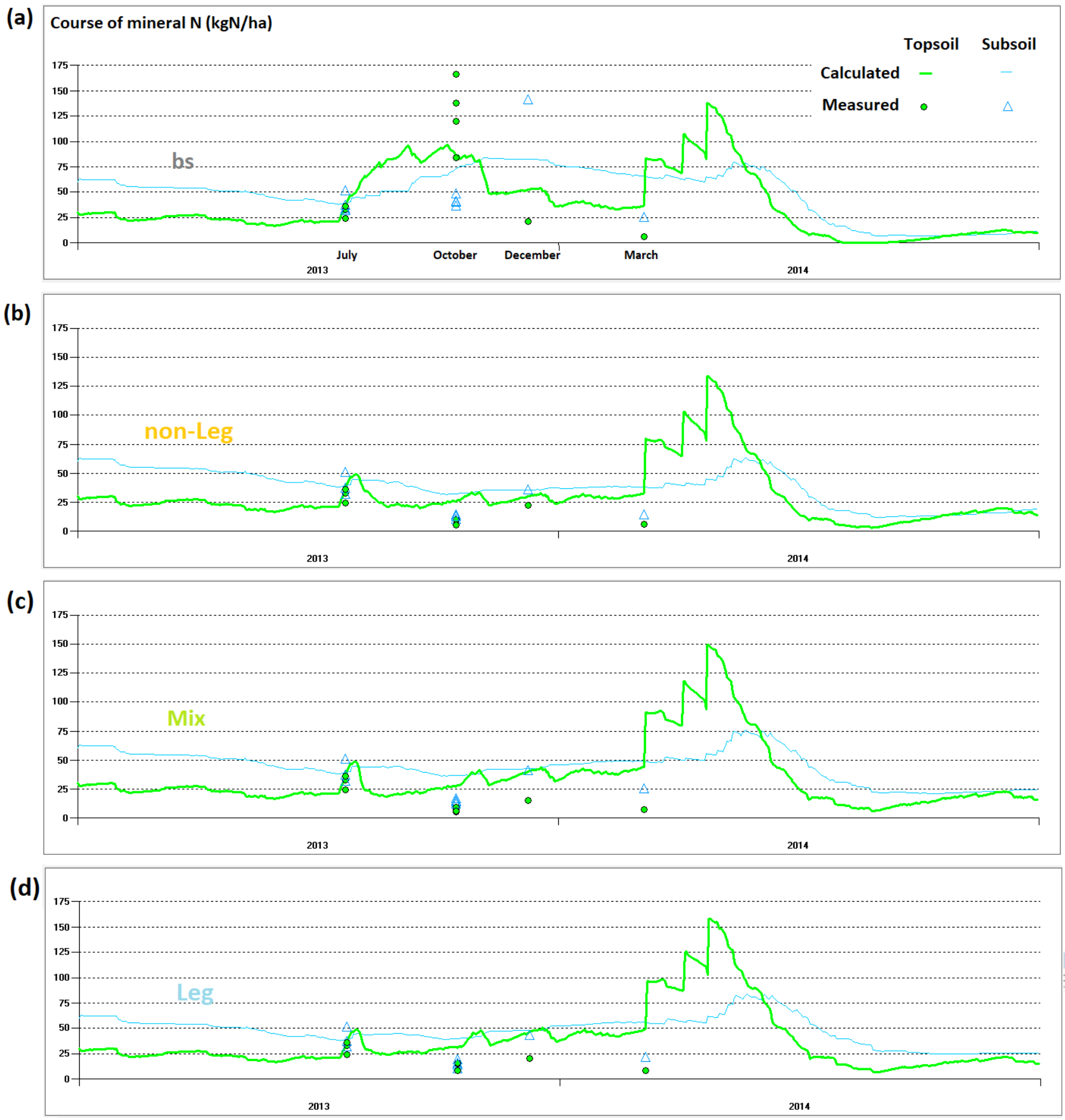

Figure 7- Comparison of mineral nitrogen simulations with NDICEA with field measured mineral nitrogen for bare soil (a), non-Leg (b), Mix (c) and Leg (d). 4 composite nitrate samplings were taken in July and October, 1 in December and March. The corresponding measurements are represented on the graphs.

[All data in kg/ha] Irrigatie	non-Leg N	bs N	Leg N	Mix N
Manure suplied	77	77	77	77
Nitrogen fixation	140	140	168	178
Irrigatie	0	0	0	0
Deposition	25 +	25 +	25 +	25 +
Total supply	**242**	**242**	**270**	**280**
Product removal	149 -	153 -	153 -	155 -
Calculated remainder	**93**	**89**	**117**	**125**
Volatilization	**6**	**6**	**6**	**6**
Denitrification	**16**	**16**	**18**	**19**
Leaching / denitrification subsoil	**41**	**85**	**71**	**60**
Increase / decrease soil organic N	**63**	**23**	**51**	**70**
Increase / decrease soil mineral N	**-29**	**-35**	**-25**	**-25**

Figure 8- Comparison of simulated nitrogen balance for CC categories and bare soil (control) with NDICEA. The values are average values on the two years of the cropping season. "Manure" refers here to mineral fertilizer/

3.7. WW plant density

In autumn 2014, the WW plant density for control and buckwheat CC were very consistent across blocks and nearly equal to the usual target plant density of 250 plants/m². All the other CC factor levels give higher variability and lower result (Figure 9). The white oat CC level should be ignored due to re-growth of oat that can't be distinguished at that stage from wheat plants. Plot with lopsided oat-egyptian clover mix had an almost significantly lower WW plant density than control and buckwheat. It also had the lowest yield this cropping season. There were no significant differences between CC categories (Table 5).

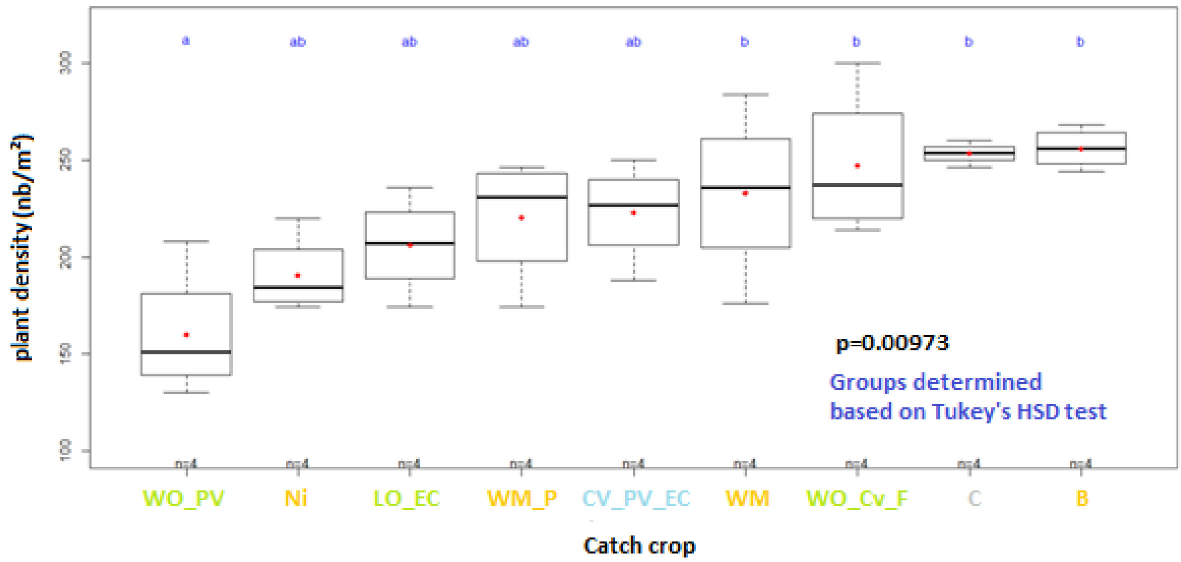

Figure 9- Effect of CC composition on WW plant density. ANOVA 1 factor was used. p=0.008134. Differences between control (C) or buckwheat (B) and white oat-purple vetch (WO_PV) respectively significant at p=0.087and p=0.073.

3.8. Wheat yield

Average yield varied greatly across years, from 9.05t/ha in 2016 to 12.16t/ha in 2014. The plots with bare soil had systematically higher yield than the plots with Mix (-0.6t/ha in average) or non-Leg CC (-0.3t/ha in average) (see Figure 10). This difference was found significant for Mix but not for non-Leg (see Table 5). No systematic differences could be observed between Mix and non-Leg. The two years

WW following Leg was tested, WW had the highest yield of all experiements, especially in 2015. It was found significantly higher than Mix (+0.8 t/ha in average) and significantly higher at p=0.073 than non-Leg (+0.5t/ha in average). No significant differences could be found with the control.

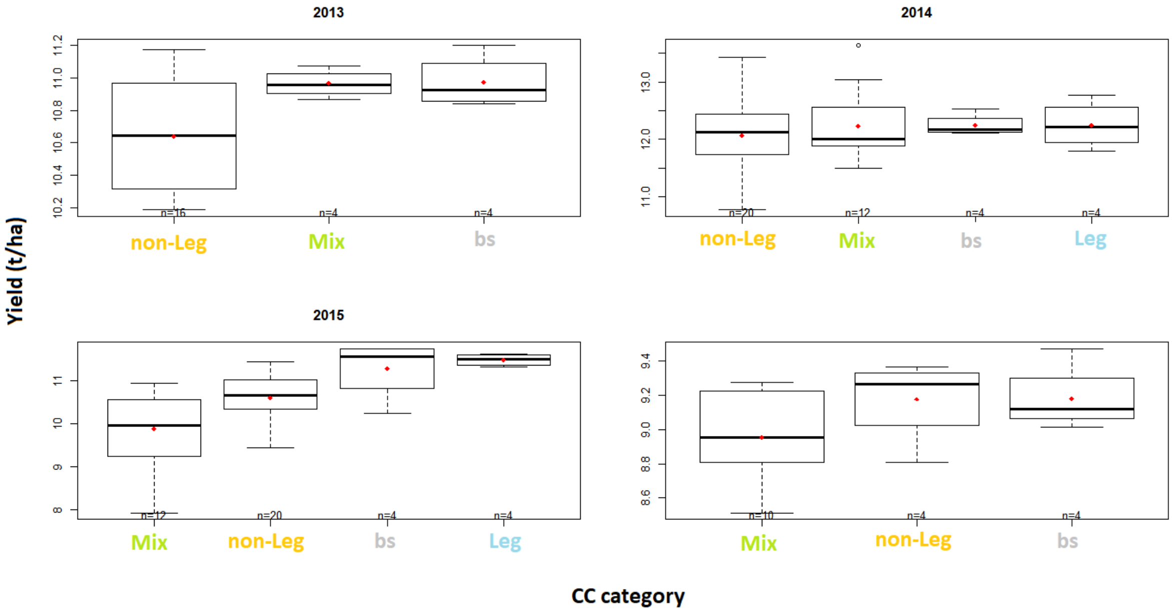

Figure 10- WW yield per year and per category. . = average value ; n=the number of individual data point included. The scale of each plot is adapted to each year performance.

If we look at the CC composition level, the four lowest WW yields were found for the CC that contained white or lopsided oat (-0.4 to -0.7t/ha compared to control), the lowest yield being found for pure white oat (Figure 11). WW following niger gave similar yield than when following CC with oat. Plots with pure white mustard, white mustard-phacelia mix and pure buckwheat had the highest yields after the control and the pure legume mix.

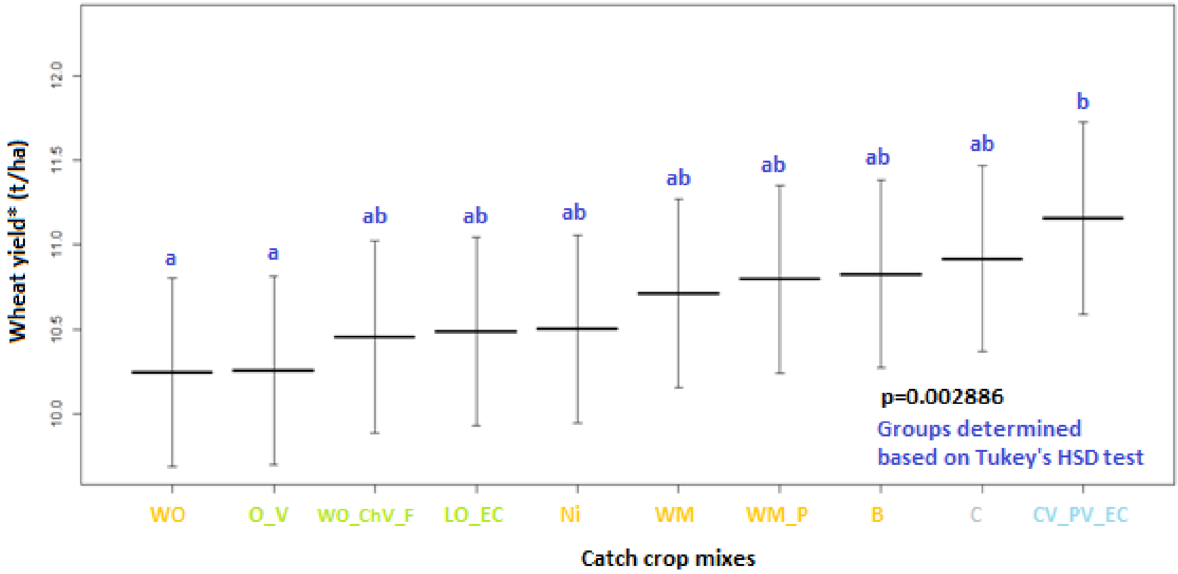

Figure 11- Effect of CC composition on WW yield. Linear mixed model was used. The groups were determined with the Tukey's HSD test, based on the least square means (horizontal lines in the graph) calculated from the model (α≤0.05). Differences between control (C) and white oat (WO) or oat-vetch (O_V) were significant at p=0.0535 and p=0.0619 respectively. The bars represent the standard error associated with the least square means.

We tested the influence of the CC total mineral N uptake indicator ($Nmin_{upt}$) on the WW yield. The increase of the CC mineral N uptake indicator in autumn had a significant negative influence on WW yield (see Table 4). 4.52kg of wheat grain was lost per kilo of CC nitrogen indicator increase (Appendix 14).

In 2015, WW yield for control was found significantly higher than for white mustard-phacelia and white oat-common vetch CC at 0kgN/ha fertilization. This difference was not found anymore at higher fertilization level (Figure 12). For fertilization level null and 100kgN/ha, WW following lopsided oat-egyptian clover CC had at least a 0.3t/ha higher average yield than when following other CC.

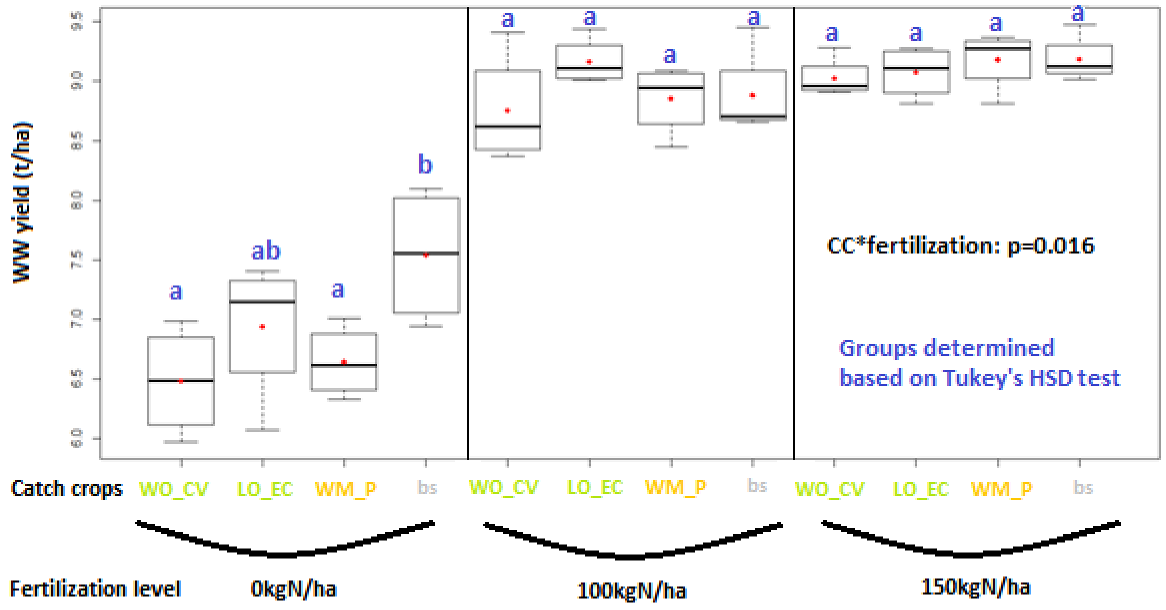

Figure 12-WW yield per CC and per fertilization level in 2016. ANOVA for split-block design was used. The groups were determined with the Tukey's HSD test, based on the least square means calculated from the model (α≤0.05).

3.9. Marginal influence of CC on economic margin

In average, the loss due to CC represents 5.7% of the semi-gross margin for control plots (1795€/ha). The use of any CC tested during more than 1 year resulted in an economic loss compared to bare soil control (see Figure 13). On average, gross margin loss per hectare with non-Leg was half of the loss with Mix and 15% less than the loss for Leg. The CC with the highest performances were white mustard-phacelia mix (2% loss) and pure white mustard (2.5% loss).

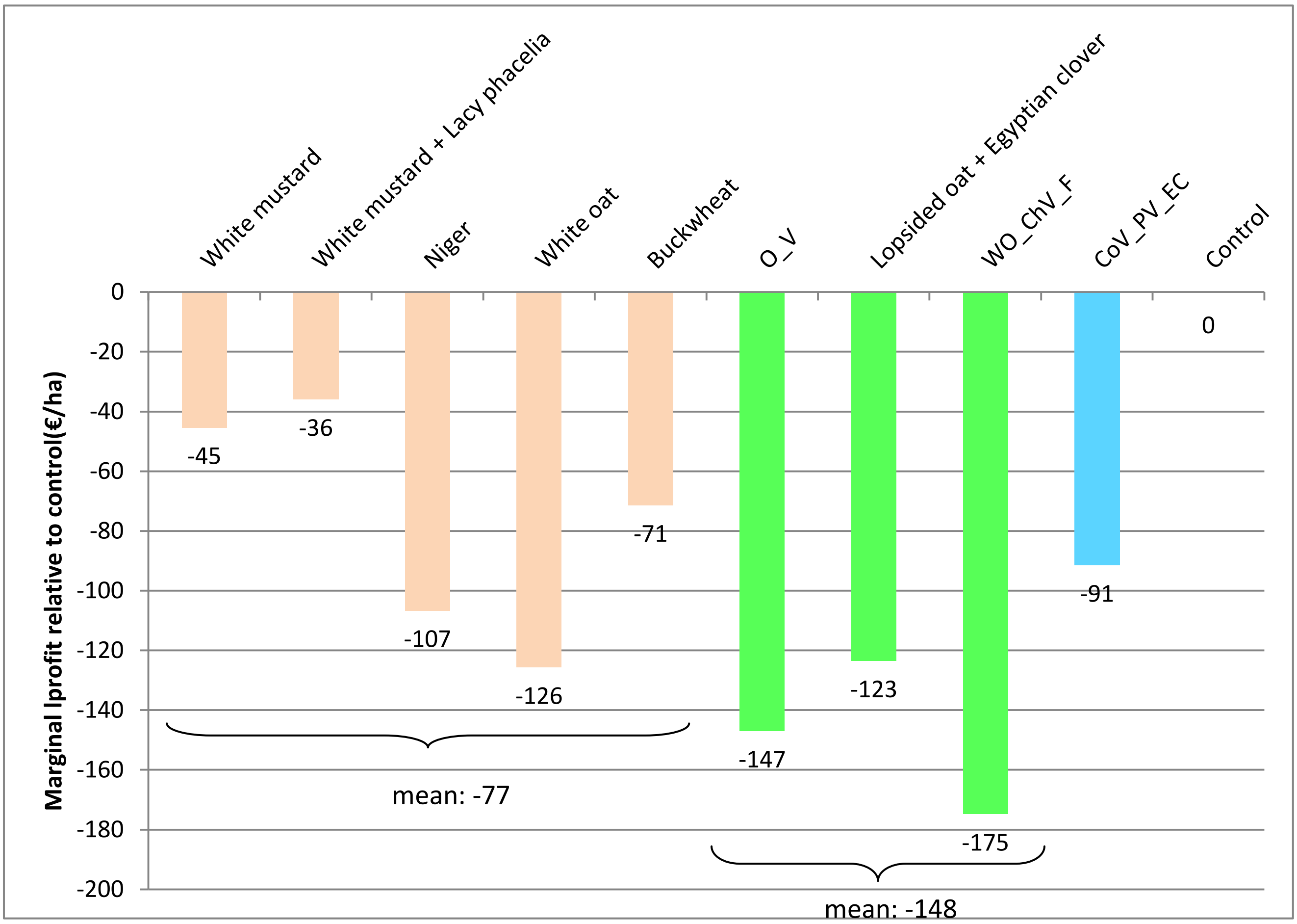

Figure 13 - Comparison of marginal economic loss of CC use relative to bare soil control. The calculations are based on CC seed costs, seeding rate, yield corrected by year effect and average wheat price on the last 3 years. Orange=No-Legumes CC, Green=Legumes and no leguminous CC mix, Blue=pure legumes CC. O_V=Oat+Vetch, WO_ChV_F=White Oat+Chickling Vetch+Fenugreek, CoV_PV_EC=Common Vetch+Purple Vetch+Egyptian Clover.

4. Discussion

4.1. General

All CC reduced soil nitrate content before leaching period below the legal threshold every year (except one CC in one year). All CC cut the nitrate leaching indicator compared to bare soil by at least 51% (Research Question 1). The plots with Mix and Leg had similar and significantly higher nitrate leaching indicator values than with non-Leg (+12 and +14kgN-NO3/ha respectively) (RQ1).

In average, WW following any CC had lower yield than WW following bare soil intercrop except for the pure legume mix but the difference was only significant with white oat and oat-vetch mixes at p=0.062. WW after Leg had a better yield than WW following Mix (+0.8t/ha, significant) and following non-Leg (+0.5t/ha, significant at p=0.072). WW after bare soil had a significant higher yield than WW following Mix (-0.6t/ha) (RQ2). Accordingly, the use of any CC tested would result in a gross margin loss compare to leaving a bare field. The lowest loss was found for non-Leg, then Leg and the highest for Mix (RQ2).

4.2. Nitrate leaching

NDICEA showed no differences of denitrification and plant uptake between CC categories. According with data, it is likely that leaching below 90cm of the post-pea harvest mineralized nitrate did not occur before December. Therefore nitrate leaching indicators differences between treatments see should represent well real nitrate leaching differences.

On average, CC cut the nitrate leaching indicator by 65%. It is in agreement with the 768 articles review Justes et al. (2012) which found a nitrate leaching reduction by CC of at least 50% compare to bare soil.

In our trials, Leg cut nitrate leaching indicator by more than half compared to bare soil. This diminution by Leg was in average 17% less than non-Leg which is contradictory with the statement: "Legumes are half effective as non-Leg as catch crops" (Justes et al., 2012). Leg CC were present only 2 years out of 5 in our experiment. It is possible that more repetitions would show different results as Aronsson et al. (2016) reviews them as "non-reliable" for nitrate leaching reduction on the basis of Swedish studies. Their lower performance seemed due to a lower nitrate catching capacity and a higher input of nitrogen due to their N fixation property (Justes et al., 2012). It seemed also due to a higher mineralization of their residues as shown by NDICEA N balance and found in Plaza-Bonilla et al. (2017). It could also increase the mineralization of the soil organic matter due to a "priming effect". "Priming effect" is defined as an increase in C and N turnover intensity due to the presence of legumes or the continuous input of fresh organic matter (Kuzyakov, 2010).

Mix resulted in lower value of nitrate leaching indicator than non-leg but in comparable nitrate uptake indicator values. This could be explain by the simultaneously high N catching capacity and N fixation of the Mix described in Justes et al. (2014). The high amount of N fixed would partly mineralize before and during winter resulting in a higher N leaching. This phenomenon could be related to the proportion of legumes in the mix. Aronsson et al. (2016) stated that clover-grass mixtures with the seed proportion 10/90 were several times found as effective as pure grass for nitrate leaching reduction. The seed proportion in our mix was 50/50 on a seed weight basis.

However, not all CC fit to their category's behavior. Biomax behaved as a non-Leg, which could be explained by a low proportion of legumes as observed by Greenotec (pers. com., 15/07/2017) or by the complementarity of the growth pattern of its plant species as explained by Aronsson et al. (2016). Buckwheat behaved more as a Mix. Its relatively low N uptake and the quick decomposition of its residues (Thomas and Archembaud, 2013) could explain this result.

4.3. WW yield

The disappearance of yield differences with increased fertilization in 2016 seemed to indicate that the yield differences were mainly due to limiting N resources. Therefore, the higher WW yield observed after Leg compared to the other CC could be explained by a higher level of available nitrogen in the first 90cm for WW after Leg CC. Such increase in available N after Leg CC has been reported in the review article by Thorup-Kristensen et al. (2003).

However, the same phenomenon cannot explain the superior yield found in control plots over plots with Mix and non-Leg. Indeed, a higher level of available N has also been found to occur after Mix crops compared to control and the nitrogen levels post-leaching period were found to be similar. Justes et al. (2012) and Thorup-Kristensen et al. (2003) describe the concept of "pre-emptive competition" of N by CC. The mineral nitrogen taken up by the CC is not compensated by a re-mineralization, resulting in a lower mineral N availability for the subsequent cash crop than with bare soil intercrop. This process was likely occurring in our experiment as shown by the negative correlation found between the mineral nitrogen uptake indicator and WW yield. Besides, WW in bare soil plot was likely to have much higher mineral N resource than described by our data and NDICEA simulations as their roots have been found to go as deep as 150cm. They had likely access to the high nitrate amount mineralized after the green pea harvest and leached down below 90cm during autumn and winter. Hoyt and Mikkelsen (1991) looked at the soil nitrate content of a fine loamy soil every 25cm until 2m deep. They found a nitrate level between 1 and 1.5m 100kgN-NO3/ha higher for bare soil than for the CC tested (hairy vetch or rye). On a shallower soil, we could potentially find a significant higher yield for CC than for bare soil, as the nitrate would be inaccessible to cash crops after bare soil fallow period. In green pea-WW succession, ARVALIS found an average wheat yield gain of 0.7t/ha for the 30-40cm deep chalk soil of Thibie when adding CC compared to bare soil. For the same succession, they found no wheat yield gain with adding CC on the 70-100cm deep loam soil of Boigneville (Labreuche, 2017; Labreuche et al., 2007).

Contrary to what was expected, WW following non-Leg had higher yield (+0.3t/ha in average) than WW following Mix although it was not significant. This can be explained by the systematic presence of oat in the Mix. Labreuche found that CC with Poaceae could have detrimental effect on subsequent WW due to transmission of pest (Labreuche, 2013), disease (Labreuche, 2017) or allelopathic effect (pers. comm., 14/06/2017). Regrowth of white oat in the WW has also been regularly observed resulting in a competition for resources with WW. The negative effect of oat could have biased the result obtained for Mix with masking the N effect. From all CC with oat, the worst yield was the non-Leg CC (white oat) although it was not significant. Another possible explanation to the lower performance of Mix than expected could be a low share of legume biomass in a large part of the mix limiting the "green manure effect" of the legumes (Tribouillois et al., 2016).

Cereal seed germination can be hindered due to problem of sowing in the CC residues in no-till systems (Labreuche, 2007). It can cause 0.5 to 2t/ha loss in hard wheat yield according with Le Souder and Labreuche (2007). This phenomenon is likely to have occurred and affected WW yield in our experiment as shown by the reduction on WW plant density for most plots with CC compared to bare soil in 2014-2015 and the very low yield obtained for lopsided oat-Egyptian clover plots also having the lowest plant density.

4.4. Economic performance

We have shown in this experiment that water protection from nitrate pollution in green pea-WW succession come at a cost for the farmers. This cost varies from 36 to 175 €/ha. It is sensibly higher that the 20 to 45 €/ha that were announced by Labreuche et al. (2007). Besides, it does not include additional operation costs that, in reality, often occur. According with van Kempen and Pérès (2017), this cost can range from 94€/ha for tine harrow as seed bed preparation, powered harrow-disc drilling for sowing and flail mower for destruction to 45€/ha for no-till disc drilling and rolling the CC for destruction. Positive effects on gross margin can be found when the CC sowing and destruction operations are integrated to the operations systematically achieved for the cash crops and when subsequent cash crop yield is increased. For instance a benefit of 61 €/ha on the gross margin was found on shallow chalk soil at Thibie by ARVALIS (Labreuche et al., 2007).

4.5. Limits

This study suffered from several experimental limitations. No type of CC was tested every year, some only 2 years. Only one pure legumes CC composition has been tested and only on 2 years. It makes our findings difficult to generalize for other years. Besides, the CC diversity used was not representative of the potential CC diversity of each of the three categories: Mix, Leg, non-Leg. All Mix contained lopsided or white oat and their legume biomass share was unknown. It limits the generalization that can be made on the effect of other CC of the same categories. The limited duration of the study (5 years) and the high variability of CC biomass across these years have made impossible the study of its effect on WW yield and soil mineral N dynamic.

The data were not systematically collected with the same methodology and were not systematically available each year. For instance, soil sample for mineral nitrogen content analysis were sometimes collected every 30cm and for the four blocks, sometimes on 0-90cm with a unique composite sample for the four blocks. This prevented us of having a more precise analysis of the mineral N dynamic on the soil and the quality of our comparisons of the treatment effects. For instance, the unique soil mineral N sample took by CC treatment in December and March 2014-2015 resulted in only one value for Leg and control but several ones for Mix and non-Leg which made the comparison impossible for that year. WW roots were found as deep as 150cm but no soil mineral N content went that deep. It also limited our understanding of soil mineral N dynamic.

The indicators used for mineral N uptake by CC ($Nmin_{upt}$), nitrate uptake by CC ($NO3_{upt}$) and nitrate leaching ($NO3_{leached}$) have a limited accuracy as the hypothesis they are based on are not fully valid. For instance, water was not absorbed and evaporated by plants for the bare soil plot, which could have resulted in higher nitrate leaching in bare soil plots compared to plots with CC between CC sowing and CC destruction. Our indicators $Nmin_{upt}$ and $NO3_{upt}$ as we defined them would decrease with an relative increase in leaching for the bare soil plots compared to the CC plots misrepresenting CC uptake. (Labreuche et al., 2007) found a N mineralization level of 12kgN/ha in plots after white mustard CC between November and February. This kind of N mineralization process between December and March in our experiment could have increased the value of soil nitrate content in March and decreased the nitrate leaching indicator, misrepresenting the actual nitrate leaching level.

The model NDICEA was not adapted to deep soil with very deep water table. It was not able to represent well the water and mineral nitrogen in the soil. Hence it was not useable quantitatively and its result needed to be handled carefully.

This study was focused on short term effect of different CC. CC have also long term effects on soil quality, and especially on organic pool of nutrients and their further release (Bouthier et al., 2015; Constantin et al., 2011). They also have long term impacts on the pest communities (Snapp et al., 2005). As soil quality, nutrient dynamics and pest dynamics are determinant for cash crop yield, CC have indirect long term effect on yield which might offset the negative effect found for most of the CC on WW yield compared to bare soil. Due to their positive long term effect on organic nitrogen pool and mineralization, we could expect a long term increasing effect on N leaching as well. However, according with Constantin et al. (2011), CC conserve their effectiveness on nitrate leaching on the long term.

4.6. Recommendations

In our study white mustard appeared to be the best option in green pea winter wheat intercrop period. It is concealing environmental protection, yield and gross margin limited loss. White mustard was found to be one of the most efficient in reducing nitrate leaching indicator. It gave a relatively good yield while having cheap seeds and could be grown easily with combining the sowing and destruction operations with operations realized for the cash crops: (i) sowing with a candy box integrated to the green pea harvester and (ii) destroying it when preparing the seedbed for WW. However, cautious has to be taken regarding the development stage of white mustard when destroyed as its C:N ratio has been observed to rapidly drop, increasing the phenomena of "pre-emptive competition" (Thomas and Archembaud, 2013).

Further experiments need to be done with a systematic collection of the data with constant methodology and constant treatment across years in this experiment in order to confirm the result of this study. Using the same mix but with different proportion of legume seed in the mix, followed by a measure of the legume biomass share and the C:N ratio could allow to get better insight on the performance of the Mix CC and the underlying mechanism responsible for it (Tribouillois et al., 2016). The measure of the soil mineral N content up on 150cm is needed in order to understand the N dynamics, assess better the nitrate leaching and the difference in yields between the different CC treatments. Testing different time of killing and incorporation of the residues would give essential information for farmers to manage their CC with limited yield loss yield increase (Thorup-Kristensen et al., 2003). Long term experiments are needed to understand the long term impact of these practices on cash crop yield, nitrate leaching but also on other aspect relevant economically such as pest suppression and N fertilization need. This new knowledge is also essential to discuss the relevance of the Walloon legislation on the nitrate content level in autumn and on the legume seed weight level policy.

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Appendices

Appendix 1- Experimental fields elevation and soil

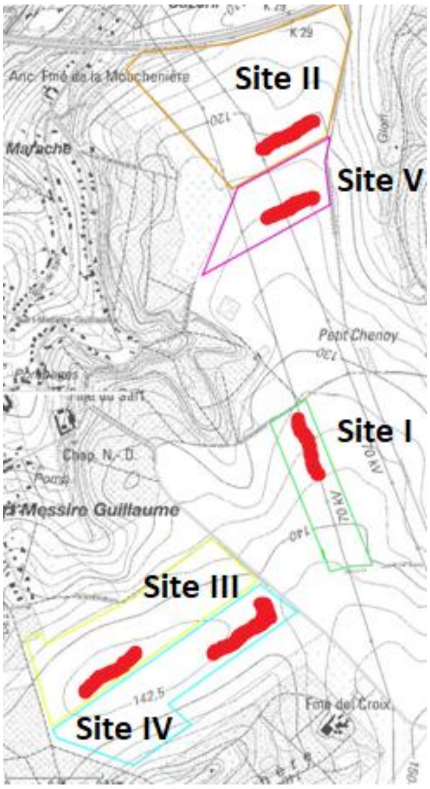


Figure 14- Topographical map of experimental sites. The colored frames indicate the farmer fields that hosted the trials. The red surfaces indicate the position of the trials in the fields. (Source: portail SIG DGARNE, 2017)

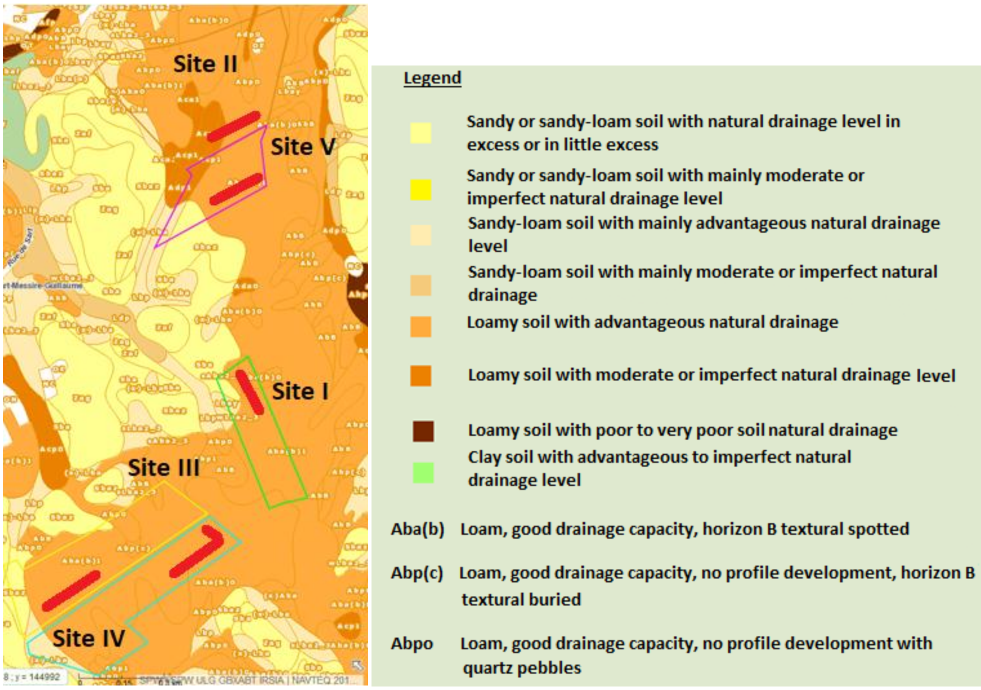


Figure 15- Soil map of experimental sites. The colored frames indicate the farmer fields that hosted the trials. The red surfaces indicate the position of the trials in the fields. (Source: portail SIG DGARNE, 2017)

Appendix 2– Cultivation practice calendars 2012-2017

2 representative years are shown here.

Table 8- Cultivation practices 2012-2013

Date	Opération culturale	Modalité
12/07/2012	Green pea harvest	/
22/07/2012	Distribution of pea residues	Cultimulch Techmagri
24/07/2012	Seed bed preparation Catch crops sowing	Lemken Smaragd 8 cm Rotative harrow Machio + rouleau packer Disc driller Accord
08/08/2012	Catch crops (CC) sowing	2nd sowing of Nigerdu nyger (issues for the first sowing)
20/10/2012	CC destruction	Flailmower Omarv TTF (Cf photo 5)
22/10/2012	Winter wheat sowing	Cultisoc + disck driller Alpégo Cultivar Edgar 140kg/ha
08/03/2013	Mineral N fertilisation	40 kgN/ha (N39)
27/03/2013	Mineral N fertilisation	40 kgN/ha (N39)
14/04/2013	Pesticide application	300 ml/ha d'Atlantis 2 kg/ha de ammonia sulfate 1 l/ha d'actirob
20/04/2013	Pesticide application	1 l/ha de stabilan 2 kg/ha de sulfate de magnésie
27/04/2013	Mineral fertilisation + Pesticide application	40 units (N39) 0.3 l/ha de stabilan 60 ml/ha de primus

22/05/2013	Pesticide application + Foliar fertilization	0.35 l/ha de rubric 0.1 l/ha d’amistar 0.2 l/ha de mirage 45 EC 1.2 l/ha d’epsotop magnesium sulfate 51 l/ha ; 85% air moisture ; wind speed 10 km/h
04/06/2013	Pesticide application + Foliar fertilization	0.4 l/ha de fandango pro 1.2 kg/ha d’epsotop MgSO4 1.2 kg/ha d’ epsotop combitop 1.2 kg/ha d’epsotop microtop 85% air moisture ; 13 km/h wind speed
04/06/2013	Mineral N fertilization	40 kgN/ha (N 27%) solid
18/06/2013	Pesticide application + Foliar fertilization	0.5 l/ha de prosaro 0.1 l/ha d’amistar 0.25 l/ha de bravo 0.5 kg/ha d’epsotop MgSO4 0.5 kg/ha d’ epsotop combitop 0.5 kg/ha d’ epsotop microtop
05/08/2013	Winter wheat harvest	With experimental harvester Redebel

Table 9- Cultivation practices 2014-2015

Date	Opération culturale	Modalité
12/07/2014	Green pea harvest	/
15/07/2014	Green residues harvest	
17/07/2014	Seedbed preparation Catch crop sowing	Lemken Smaragd 8 cm Herve rotative Machio + rouleau packer Disc driller Accord
01/10/2014	Catch crops destruction	Flail mower Omarv TTF
03/10/2014	Seed bed preparation	Lemken Smaragd 8 cm
04/10/2014	Winter wheat sowing	Cultisoc + disc driller Alpégo Variété Edgar 140kg/ha
02/11/2014	Pesticide application	1 l/ha baccara
24/11/2014	Pesticide application	1l/ha lambda stefes
19/03/2015	Mineral N fertilisation	50 kgN/ha sulfazote (N 22% - SO_3 7.5%)
10/04/2015	Pesticide application	1 l/ha stabilan 0.11 l/ha modus
20/04/2015	Mineral N fertilisation	60 kgN/ha sulfazote (N 22% - SO_3 7.5%)
04/05/2015	Mineral N fertilisation	57 kgN/ha sulfazote (N 22% - SO_3 7.5%)
05/05/2015	Pesticide application	0.35 l/ha de rubric 0.5 l/ha pugil 1.1 kg/ha d’epsotop
23/05/2015	Pesticide application	0.9 l/ha cériax
03/08/2015	Winter wheat sowing	Redebel experimental harvester

Table 10- Catch crops sowing rates

Cover crops (single-species or mixtures)	Sowing rates (kg/ha)				
Common names	**2012-2013**	**2013-2014**	**2014-2015**	**2015-2016**	**2016-2017**
White mustard	8	8	8		
White mustard + Lacy phacelia		1+4	1+4	2 +4	2+4
Niger	8	11	11		
White oat		100	100		
White oat+ Common spring vetch	80+20			80+20	80+20
Lopsided oat + Purple vetch		80+20	80+20		
Common spring Vetch	60				
Common vetch+ Purple vetch + Egyptian clover		40	40		
Buckwheat + Egyptian clover	10+10				
Buckwheat	20	27	27		
Lopsided oat + Egyptian clover		20+10	20+10	20+10	20+10
White oat+Chickling vetch+Fenugreek		70+30+20	70+30+20		
White mustard+Lacy phacelia+Niger+Sunflower+Common Vetch				1+3+4+5+13	1+3+4+5+13

Appendix 3 - Data structure description

Table 11- Summary of data structure for CCE and CCFE trials

		2013/Site1	2014/Site 2	2015/ Site 3	2016/Site 4	2017/Site 5
Number of factors (Nb of levels)		1 (5) : CC	1 (10) : CC	1(10) : CC	2 (3 et 4) : CC and fertilisation level	2 (3 et 4) : CC and fertilisation level
Nb of treatments		6	10	10	12	12
Nb de blocks		4	4	4	4	4
Nb of plots		24	40	40	48	48
Nb of samples per treatments for each response	Mineral N content in July (kgN/ha)	1[1][3]	1[1][4]	1[1][3]	1[1][4]	*NA*
	Mineral N content in October (kgN/ha)	1[1]	1[1]	1[1]	1[1][6]	1[1] [6]
	Mineral N content in December (kgN/ha)	0,25[1][5]	0,25[1] [5]	1[2]	1[1] [6]	1[2] [6]

	Mineral N content in December (kgN/ha)	0,25[1]	0,25[1]	1[2]	1[2] [6]	1[2] [6]
	CC biomass (t/ha)	1	1	1	1	1
	Wheat plant density (nb/m²)	*NA*	*NA*	2	*NA*	*NA*
	WW yield (t/ha)	1	1	1	1	*NA*
Total number of measurements per response variable	Mineral N content in July (kgN/ha)	1[1]	4[1]	1[1]	4[1]	*NA*
	Mineral N content in October (kgN/ha)	24	40	40[1]	16[1]	16[1]
	Mineral N content in December (kgN/ha)	4 [7]	10	40	16	16
	Mineral N content in December (kgN/ha)	6	10	40	16	16
	CC biomass (t/ha)	20	36	36	44	44
	Wheat plant density (nb/m²)	*NA*	*NA*	80	*NA*	*NA*
	WW yield (t/ha)	24	40	40	48	*NA*

NA = « no data available» ; [1] sample every 30cm ; [2] sample on 90cm ; [3] 1 sample for the all trial; [4] 1 sample per block ; [5] 1 sample per treatment [6] 1 sample per CC factor level (no fertilization has been applied still) [7] 1 sample per treatment for 4 of the treatments.

Appendix 4- Walloon reference levels of soil nitrate content pre-leaching period

Table 12- Walloon reference levels of soil nitrate content in October and December (GRENeRA and U. C.L. 2016, 2015, 2014, 2013, 2012)

	Aimed level (kgN-NO3/ha)		Acceptable level (kgN-NO3/ha)		Intervention threshold (kgN-NO3/ha)	
	October	December	October	December	October	December
2012	63	75	113	106	128	121
2013	62	66	78	78	93	93
2014	95	89	106	102	125	120
2015	36	65	66	73	81	88
2016	46	57	78	89	93	104

Appendix 5- Cross year data set

Bloc	CC	Year	Biomass	NO3_uptake	NO3_2	NO3_3	NO3_4	NO3_leached	NH4_uptake	WW_yield	leg
B1	WO	2013	2.76630972	108.49	10.06	NA	39.32	NA	3.21	10.206	non-Leg
B2	WO	2013	2.846852732	126.87	14.43	NA	39.32	NA	1.37	10.339	non-Leg
B3	WO	2013	2.671774592	141.47	40.03	NA	39.32	NA	0.94	10.329	non-Leg
B4	WO	2013	4.092256714	132.64	7.4	NA	39.32	NA	6.38	10.599	non-Leg
B1	WM	2013	5.622982569	113.42	5.13	56.89	30.79	26.1	1.01	10.309	non-Leg
B2	WM	2013	5.656537102	135.73	5.57	56.89	30.79	26.1	-1.64	11.173	non-Leg
B3	WM	2013	5.315656229	177.44	4.06	56.89	30.79	26.1	0.51	10.288	non-Leg
B4	WM	2013	5.278963992	130.97	9.07	56.89	30.79	26.1	4.36	10.72	non-Leg
B1	Ni	2013	2.949678801	101.5	17.05	62.98	35.94	27.04	3.17	10.691	non-Leg
B2	Ni	2013	3.145050916	99.41	41.89	62.98	35.94	27.04	-5.9	10.189	non-Leg
B3	Ni	2013	3.098637973	164.36	17.14	62.98	35.94	27.04	-0.26	10.572	non-Leg
B4	Ni	2013	2.742293992	126.31	13.73	62.98	35.94	27.04	6.54	10.921	non-Leg
B1	B	2013	4.398377648	106.96	11.59	NA	26.46	NA	6.33	11.015	non-Leg
B2	B	2013	4.209127382	106.21	35.09	NA	26.46	NA	2.91	11.109	non-Leg
B3	B	2013	4.961672843	147.14	34.36	NA	26.46	NA	2.45	11.029	non-Leg
B4	B	2013	4.469569203	106.38	33.66	NA	26.46	NA	6.36	10.712	non-

											Leg
B1	C	2013	NA	NA	118.55	148.67	64.73	83.94	0	10.87	bs
B2	C	2013	NA	NA	141.3	148.67	64.73	83.94	0	10.838	bs
B3	C	2013	NA	NA	181.5	148.67	64.73	83.94	0	11.198	bs
B4	C	2013	NA	NA	140.04	148.67	64.73	83.94	0	10.979	bs
B1	WO	2014	3.822724138	163.09	8.3	54.89	17.95	36.94	0.0899999999999999	10.775	non-Leg
B2	WO	2014	4.605472414	102.73	11.89	54.89	17.95	36.94	-0.99	12.094	non-Leg
B3	WO	2014	5.151575862	192.12	16.69	54.89	17.95	36.94	-2.11	12.211	non-Leg
B4	WO	2014	7.663651724	141.41	11.72	54.89	17.95	36.94	2.51	12.358	non-Leg
B1	O_V	2014	6.638725275	157.04	14.35	83.76	31.24	52.52	-0.58	11.856	Mix
B2	O_V	2014	5.415802198	88.66	25.96	83.76	31.24	52.52	-1.95	13.633	Mix
B3	O_V	2014	4.75192967	158	50.81	83.76	31.24	52.52	-4.01	11.917	Mix
B4	O_V	2014	7.127894505	119.19	33.94	83.76	31.24	52.52	1.97	12.479	Mix
B1	LO_EC	2014	2.434067692	158.26	13.13	54.66	26.54	28.12	0.65	11.92	Mix
B2	LO_EC	2014	2.160235077	99.05	15.57	54.66	26.54	28.12	-2.11	12.038	Mix
B3	LO_EC	2014	4.031424615	197.18	11.63	54.66	26.54	28.12	-1.17	11.967	Mix
B4	LO_EC	2014	3.529398154	133.86	19.27	54.66	26.54	28.12	0.119999999999999	12.225	Mix
B1	WO_ChV_F	2014	4.464246254	155.85	15.54	61.4	24.85	36.55	3.45	11.493	Mix
B2	WO_ChV_F	2014	5.360754723	94.07	20.55	61.4	24.85	36.55	-4.89	11.652	Mix
B3	WO_ChV_F	2014	6.67807329	182.82	25.99	61.4	24.85	36.55	-3.15	13.041	Mix
B4	WO_ChV_F	2014	6.257263192	138.68	14.45	61.4	24.85	36.55	-2.17	12.634	Mix
B1	WM	2014	4.220640244	164.83	6.56	44.74	16.99	27.75	1.72	10.927	non-Leg
B2	WM	2014	4.722223577	105.66	8.96	44.74	16.99	27.75	-6.29	12.281	non-Leg
B3	WM	2014	6.165804878	202.51	6.3	44.74	16.99	27.75	-1.84	12.17	non-

											Leg
B4	WM	2014	5.99453252	139.17	13.96	44.74	16.99	27.75	1.56	12.525	non-Leg
B1	WM_P	2014	2.988163636	164.69	6.7	66.31	23.04	43.27	2.32	11.781	non-Leg
B2	WM_P	2014	5.994772727	102.29	12.33	66.31	23.04	43.27	-3.23	13.089	non-Leg
B3	WM_P	2014	5.090945455	199.87	8.94	66.31	23.04	43.27	-10.21	11.355	non-Leg
B4	WM_P	2014	7.691754545	139.51	13.62	66.31	23.04	43.27	0.0999999999999979	13.435	non-Leg
B1	Ni	2014	4.471287831	159.14	12.25	39.77	13.26	26.51	1.53	11.97	non-Leg
B2	Ni	2014	4.965601058	99.18	15.44	39.77	13.26	26.51	-4.3	12.687	non-Leg
B3	Ni	2014	4.763382011	188.94	19.87	39.77	13.26	26.51	-2.16	11.892	non-Leg
B4	Ni	2014	5.796946032	137.72	15.41	39.77	13.26	26.51	3.48	11.995	non-Leg
B1	B	2014	2.208717021	157.82	13.57	53.47	10.29	43.18	1.55	11.68	non-Leg
B2	B	2014	2.814332979	86.62	28	53.47	10.29	43.18	0.850000000000001	11.317	non-Leg
B3	B	2014	3.847442553	183.22	25.59	53.47	10.29	43.18	-2.9	12.196	non-Leg
B4	B	2014	4.310560638	120.29	32.84	53.47	10.29	43.18	-1.12	12.67	non-Leg
B1	C	2014	NA	NA	171.39	155.49	29.15	126.34	0	12.536	bs
B2	C	2014	NA	NA	114.62	155.49	29.15	126.34	0	12.191	bs
B3	C	2014	NA	NA	208.81	155.49	29.15	126.34	0	12.11	bs
B4	C	2014	NA	NA	153.13	155.49	29.15	126.34	0	12.137	bs
B1	CoV_PV_EC	2014	3.284365714	151.41	19.98	82.82	36.65	46.17	2.19	12.097	Leg

B2	CoV_PV_EC	2014	4.86144	71.13	43.49	82.82	36.65	46.17	-3.03	11.795	Leg
B3	CoV_PV_EC	2014	3.429051429	166.4	42.41	82.82	36.65	46.17	-7.44	12.772	Leg
B4	CoV_PV_EC	2014	4.326102857	114.14	38.99	82.82	36.65	46.17	-6.63	12.335	Leg
B1	WO	2015	5.804094479	118.58	13.56	47.72	23.06	24.66	11.34	9.811	non-Leg
B2	WO	2015	5.123905025	80.38	56.44	61.98	15.63	46.35	-2.66	10.212	non-Leg
B3	WO	2015	5.183237815	134.43	21.19	71	34.36	36.64	7.97	10.476	non-Leg
B4	WO	2015	5.020337013	146.8	12.13	34.06	26.36	7.7	27.08	9.435	non-Leg
B1	O_V	2015	4.303748798	119.99	12.15	62.21	34.04	28.17	6.66	7.933	Mix
B2	O_V	2015	4.466864082	122.06	14.76	44.32	49.24	-4.92	-3.15	9.062	Mix
B3	O_V	2015	5.188705619	142.61	13.01	74.13	26.07	48.06	8.23	9.987	Mix
B4	O_V	2015	4.751203852	144.1	14.83	50.24	28.73	21.51	24.31	9.885	Mix
B1	LO_EC	2015	3.961610765	106.9	25.24	99.88	31.82	68.06	11.07	9.11	Mix
B2	LO_EC	2015	4.249806051	94.8	42.02	81.92	24.53	57.39	1.57	10.498	Mix
B3	LO_EC	2015	3.535979724	111.5	44.12	64.35	21.26	43.09	-8.78	10.637	Mix
B4	LO_EC	2015	2.785025087	127.92	31.01	66.73	31.52	35.21	23.72	10.928	Mix
B1	WO_ChV_F	2015	4.402752998	99.86	32.28	103.2	34.27	68.93	-4.15	10.736	Mix
B2	WO_ChV_F	2015	4.883829306	116.74	20.08	67.91	33.72	34.19	-3.9	9.388	Mix
B3	WO_ChV_F	2015	4.833647044	128.79	26.83	64.74	31.32	33.42	0.57	9.926	Mix
B4	WO_ChV_F	2015	4.961643939	141.93	17	41.51	15.72	25.79	24.32	10.416	Mix
B1	WM	2015	4.672698696	117.94	14.2	33.65	10.95	22.7	5.43	10.669	non-Leg
B2	WM	2015	3.060461432	120.08	16.74	36.59	11.76	24.83	2.76	11.433	non-Leg
B3	WM	2015	4.058893351	129.17	26.45	40.1	10.86	29.24	-3.73	11.104	non-Leg
B4	WM	2015	4.083680716	136.98	21.95	43.28	15.88	27.4	18.9	10.861	non-Leg

B1	WM_P	2015	4.073831199	87.99	44.15	40.43	8.68	31.75	-13.85	10.938	non-Leg
B2	WM_P	2015	3.802597815	120.96	15.86	35.72	16.17	19.55	-8.14	10.339	non-Leg
B3	WM_P	2015	3.361068111	142.44	13.18	63.01	27.23	35.78	-5.66	11.022	non-Leg
B4	WM_P	2015	3.920446664	144.67	14.26	41.66	11.46	30.2	18.26	10.64	non-Leg
B1	Ni	2015	4.674677052	120.79	11.35	32.22	19.97	12.25	13.83	10.498	non-Leg
B2	Ni	2015	4.453152079	120.4	16.42	55.9	21.51	34.39	-2.81	10.337	non-Leg
B3	Ni	2015	4.747701736	113.49	42.13	49.29	25.12	24.17	-23.74	10.539	non-Leg
B4	Ni	2015	5.210271678	142.47	16.46	28.96	19.97	8.99	27.8	9.638	non-Leg
B1	B	2015	3.961610765	111.22	20.92	44.04	14.11	29.93	13.67	10.692	non-Leg
B2	B	2015	4.249806051	103.46	33.36	58.29	20.48	37.81	6.24	11.298	non-Leg
B3	B	2015	3.66548063433333	118.35	24.28	49.9166666666667	15.9566666666667	33.96	17.4333333333333	11.0266666666667	non-Leg
B4	B	2015	2.785025087	140.37	18.56	47.42	13.28	34.14	32.39	11.09	non-Leg
B1	C	2015	NA	NA	132.14	144.42	12.24	132.18	0	10.247	bs
B2	C	2015	NA	NA	136.82	115.69	20.45	95.24	0	11.736	bs
B3	C	2015	NA	NA	155.62	146.09	38.06	108.03	0	11.722	bs
B4	C	2015	NA	NA	158.93	97.13	16.83	80.3	0	11.407	bs
B1	CoV_PV_EC	2015	2.421242981	52.39	79.75	105.41	48.38	57.03	13.46	11.585	Leg
B2	CoV_PV_EC	2015	2.394762998	86.71	50.11	80.78	77.83	2.95	-10.17	11.612	Leg
B3	CoV_PV_EC	2015	1.887010309	86.82	68.8	71.13	14.59	56.54	7.24	11.324	Leg

B4	CoV_PV_EC	2015	1.554979637	107.02	51.91	79.86	15.41	64.45	20.39	11.392	Leg
B1	O_V	2016	2.329	91.64	19.93	62.35	7.31	55.04	0.28	8.965	Mix
B2	O_V	2016	2.466	80.61	21.32	106.14	7.65	98.49	-5.42	9.277	Mix
B3	O_V	2016	2.859	75.5	27.21	86	5.16	80.84	-2.15	8.938	Mix
B4	O_V	2016	2.258	84.83	40.42	52.15	6.4	45.75	0.48	8.905	Mix
B1	LO_EC	2016	1.776505231	83.85	27.72	83.32	10.33	72.99	2.01	8.809	Mix
B2	LO_EC	2016	2.260432486	56.99	44.94	86.31	6.2	80.11	-3.82	9.267	Mix
B3	LO_EC	2016	2.032902848	68.03	34.68	68.81	7.07	61.74	0.68	9.224	Mix
B4	LO_EC	2016	1.077128555	85.91	39.34	117.07	5.93	111.14	1.89	8.982	Mix
B1	WM_P	2016	2.521	103.41	8.16	53.46	6.23	47.23	-0.39	8.81	non-Leg
B2	WM_P	2016	2.713	84.85	17.08	58.64	7.16	51.48	-1.18	9.299	non-Leg
B3	WM_P	2016	2.416	90.62	12.09	39.18	6.05	33.13	-0.4	9.235	non-Leg
B4	WM_P	2016	2.813	117.93	7.32	57.45	5.9	51.55	0.86	9.364	non-Leg
B1	C	2016	NA	NA	111.57	104.88	6.44	98.44	0	9.013	bs
B2	C	2016	NA	NA	101.93	58.87	9.94	48.93	0	9.471	bs
B3	C	2016	NA	NA	102.71	41.03	5.57	35.46	0	9.116	bs
B4	C	2016	NA	NA	125.25	106.31	6.55	99.76	0	9.125	bs
B1	Biomax	2016	3.041	99.95	10.53	41.81	14.36	27.45	-1.91	8.64236524247341	Mix
B2	Biomax	2016	2.891	84.09	20.56	52.36	14.13	38.23	-2.95	8.51365015166835	Mix
B1	O_V	2017	2.586963146	NA	10.2	52.92	30.52	22.4	NA	NA	Mix
B2	O_V	2017	2.731077713	NA	20.66	50.62	40.95	9.66999999999999	NA	NA	Mix
B3	O_V	2017	3.114185368	NA	41.64	74.51	28.4	46.11	NA	NA	Mix
B4	O_V	2017	2.305394057	NA	15.98	57.46	30.19	27.27	NA	NA	Mix
B1	LO_EC	2017	2.731145059	NA	NA	64.6	50.78	13.82	NA	NA	Mix

B2	LO_EC	2017	3.387425849	NA	31.4	81.38	57.82	23.56	NA	NA	Mix
B3	LO_EC	2017	3.002387574	NA	12.44	109.68	43.18	66.5	NA	NA	Mix
B4	LO_EC	2017	2.935355939	NA	15.84	80.04	54.46	25.58	NA	NA	Mix
B1	WM_P	2017	4.979330474	NA	5.29	17.8	18.28	-0.48	NA	NA	non-Leg
B2	WM_P	2017	4.510042865	NA	8.06	27.46	21.93	5.53	NA	NA	non-Leg
B3	WM_P	2017	4.775906723	NA	3.88	31.03	47.33	-16.3	NA	NA	non-Leg
B4	WM_P	2017	5.433040936	NA	6.38	21.67	11.78	9.89	NA	NA	non-Leg
B1	C	2017	NA	NA	164.07	151.04	65.63	85.41	NA	NA	bs
B2	C	2017	NA	NA	143.37	221.93	62.68	159.25	NA	NA	bs
B3	C	2017	NA	NA	58.27	173.16	91.28	81.88	NA	NA	bs
B4	C	2017	NA	NA	124.71	128.9	76.67	52.23	NA	NA	bs
B1	Biomax	2017	7.144	NA	4.78	21.97	20.97	1	NA	NA	Mix
B2	Biomax	2017	6.408	NA	7.64	20.69	22.42	-1.73	NA	NA	Mix

Appendix 6- CCE dataset 2012-2013

Bloc	CC	Biomass	NO3_uptake	NO3_2	NO3_3	NO3_4	NO3_leached	NH4_uptake	WW yield
B1	WO	2.76630972	108.49	10.06	NA	39.32	NA	3.21	10.206
B2	WO	2.846852732	126.87	14.43	NA	39.32	NA	1.37	10.339
B3	WO	2.671774592	141.47	40.03	NA	39.32	NA	0.94	10.329
B4	WO	4.092256714	132.64	7.4	NA	39.32	NA	6.38	10.599
B1	WM	5.622982569	113.42	5.13	56.89	30.79	26.1	1.01	10.309
B2	WM	5.656537102	135.73	5.57	56.89	30.79	26.1	-1.64	11.173
B3	WM	5.315656229	177.44	4.06	56.89	30.79	26.1	0.51	10.288
B4	WM	5.278963992	130.97	9.07	56.89	30.79	26.1	4.36	10.72
B1	Ni	2.949678801	101.5	17.05	62.98	35.94	27.04	3.17	10.691

B2	Ni	3.145050916	99.41	41.89	62.98	35.94	27.04	-5.9	10.189
B3	Ni	3.098637973	164.36	17.14	62.98	35.94	27.04	-0.26	10.572
B4	Ni	2.742293992	126.31	13.73	62.98	35.94	27.04	6.54	10.921
B1	B_EC	3.918367347	88.29	30.26	45.29	28.93	16.36	3.59	10.943
B2	B_EC	3.404187438	128.97	12.33	45.29	28.93	16.36	3.84	11.076
B3	B_EC	3.255681818	136.17	45.33	45.29	28.93	16.36	1.92	10.976
B4	B_EC	3.579179811	86.08	53.96	45.29	28.93	16.36	6.21	10.867
B1	B	4.398377648	106.96	11.59	NA	26.46	NA	6.33	11.015
B2	B	4.209127382	106.21	35.09	NA	26.46	NA	2.91	11.109
B3	B	4.961672843	147.14	34.36	NA	26.46	NA	2.45	11.029
B4	B	4.469569203	106.38	33.66	NA	26.46	NA	6.36	10.712
B1	C	NA	NA	118.55	148.67	64.73	83.94	NA	10.87
B2	C	NA	NA	141.3	148.67	64.73	83.94	NA	10.838
B3	C	NA	NA	181.5	148.67	64.73	83.94	NA	11.198
B4	C	NA	NA	140.04	148.67	64.73	83.94	NA	10.979

Appendix 7- CCE dataset 2013-2014

Block	CC	Biomass	NO3_uptake	NO3_2	NO3_3	NO3_4	NO3_leached	NH4_uptake	rendement
B1	WO	3.822724138	163.09	8.3	54.89	17.95	36.94	0.0899999999999999	10.775
B2	WO	4.605472414	102.73	11.89	54.89	17.95	36.94	-0.99	12.094
B3	WO	5.151575862	192.12	16.69	54.89	17.95	36.94	-2.11	12.211
B4	WO	7.663651724	141.41	11.72	54.89	17.95	36.94	2.51	12.358
B1	WO_PV	6.638725275	157.04	14.35	83.76	31.24	52.52	-0.58	11.856
B2	WO_PV	5.415802198	88.66	25.96	83.76	31.24	52.52	-1.95	13.633
B3	WO_PV	4.75192967	158	50.81	83.76	31.24	52.52	-4.01	11.917
B4	WO_PV	7.127894505	119.19	33.94	83.76	31.24	52.52	1.97	12.479
B1	LO_EC	2.434067692	158.26	13.13	54.66	26.54	28.12	0.65	11.92
B2	LO_EC	2.160235077	99.05	15.57	54.66	26.54	28.12	-2.11	12.038
B3	LO_EC	4.031424615	197.18	11.63	54.66	26.54	28.12	-1.17	11.967
B4	LO_EC	3.529398154	133.86	19.27	54.66	26.54	28.12	0.119999999999999	12.225

B1	WO_ChV_F	4.464246254	155.85	15.54	61.4	24.85	36.55	3.45	11.493
B2	WO_ChV_F	5.360754723	94.07	20.55	61.4	24.85	36.55	-4.89	11.652
B3	WO_ChV_F	6.67807329	182.82	25.99	61.4	24.85	36.55	-3.15	13.041
B4	WO_ChV_F	6.257263192	138.68	14.45	61.4	24.85	36.55	-2.17	12.634
B1	WM	4.220640244	164.83	6.56	44.74	16.99	27.75	1.72	10.927
B2	WM	4.722223577	105.66	8.96	44.74	16.99	27.75	-6.29	12.281
B3	WM	6.165804878	202.51	6.3	44.74	16.99	27.75	-1.84	12.17
B4	WM	5.99453252	139.17	13.96	44.74	16.99	27.75	1.56	12.525
B1	WM_P	2.988163636	164.69	6.7	66.31	23.04	43.27	2.32	11.781
B2	WM_P	5.994772727	102.29	12.33	66.31	23.04	43.27	-3.23	13.089
B3	WM_P	5.090945455	199.87	8.94	66.31	23.04	43.27	-10.21	11.355
B4	WM_P	7.691754545	139.51	13.62	66.31	23.04	43.27	0.0999999999999979	13.435
B1	Ni	4.471287831	159.14	12.25	39.77	13.26	26.51	1.53	11.97
B2	Ni	4.965601058	99.18	15.44	39.77	13.26	26.51	-4.3	12.687
B3	Ni	4.763382011	188.94	19.87	39.77	13.26	26.51	-2.16	11.892
B4	Ni	5.796946032	137.72	15.41	39.77	13.26	26.51	3.48	11.995
B1	B	2.208717021	157.82	13.57	53.47	10.29	43.18	1.55	11.68
B2	B	2.814332979	86.62	28	53.47	10.29	43.18	0.850000000000001	11.317
B3	B	3.847442553	183.22	25.59	53.47	10.29	43.18	-2.9	12.196
B4	B	4.310560638	120.29	32.84	53.47	10.29	43.18	-1.12	12.67
B1	C	NA	NA	171.39	155.49	29.15	126.34	NA	12.536
B2	C	NA	NA	114.62	155.49	29.15	126.34	NA	12.191
B3	C	NA	NA	208.81	155.49	29.15	126.34	NA	12.11
B4	C	NA	NA	153.13	155.49	29.15	126.34	NA	12.137
B1	CoV_PV_EC	3.284365714	151.41	19.98	82.82	36.65	46.17	2.19	12.097
B2	CoV_PV_EC	4.86144	71.13	43.49	82.82	36.65	46.17	-3.03	11.795
B3	CoV_PV_EC	3.429051429	166.4	42.41	82.82	36.65	46.17	-7.44	12.772
B4	CoV_PV_EC	4.326102857	114.14	38.99	82.82	36.65	46.17	-6.63	12.335

Appendix 8- CCE dataset 2014-2015

Block	CC	Biomass	NO3_uptake	NO3_2	NO3_3	NO3_4	NO3_leached	NH4_uptake	WW yield	plant density
B1	WO	5.804094479	118.58	13.56	47.72	23.06	24.66	11.34	9.811	NA
B2	WO	5.123905025	80.38	56.44	61.98	15.63	46.35	-2.66	10.212	NA
B3	WO	5.183237815	134.43	21.19	71	34.36	36.64	7.97	10.476	NA
B4	WO	5.020337013	146.8	12.13	34.06	26.36	7.7	27.08	9.435	NA
B1	WO_PV	4.303748798	119.99	12.15	62.21	34.04	28.17	6.66	7.933	130
B2	WO_PV	4.466864082	122.06	14.76	44.32	49.24	-4.92	-3.15	9.062	154
B3	WO_PV	5.188705619	142.61	13.01	74.13	26.07	48.06	8.23	9.987	208
B4	WO_PV	4.751203852	144.1	14.83	50.24	28.73	21.51	24.31	9.885	148
B1	LO_EC	3.961610765	106.9	25.24	99.88	31.82	68.06	11.07	9.11	236
B2	LO_EC	4.249806051	94.8	42.02	81.92	24.53	57.39	1.57	10.498	174
B3	LO_EC	3.535979724	111.5	44.12	64.35	21.26	43.09	-8.78	10.637	204
B4	LO_EC	2.785025087	127.92	31.01	66.73	31.52	35.21	23.72	10.928	210
B1	WO_ChV_F	4.402752998	99.86	32.28	103.2	34.27	68.93	-4.15	10.736	226
B2	WO_ChV_F	4.883829306	116.74	20.08	67.91	33.72	34.19	-3.9	9.388	248
B3	WO_ChV_F	4.833647044	128.79	26.83	64.74	31.32	33.42	0.57	9.926	300
B4	WO_ChV_F	4.961643939	141.93	17	41.51	15.72	25.79	24.32	10.416	214
B1	WM	4.672698696	117.94	14.2	33.65	10.95	22.7	5.43	10.669	176
B2	WM	3.060461432	120.08	16.74	36.59	11.76	24.83	2.76	11.433	238
B3	WM	4.058893351	129.17	26.45	40.1	10.86	29.24	-3.73	11.104	284
B4	WM	4.083680716	136.98	21.95	43.28	15.88	27.4	18.9	10.861	234
B1	WM_P	4.073831199	87.99	44.15	40.43	8.68	31.75	-13.85	10.938	240
B2	WM_P	3.802597815	120.96	15.86	35.72	16.17	19.55	-8.14	10.339	222
B3	WM_P	3.361068111	142.44	13.18	63.01	27.23	35.78	-5.66	11.022	174
B4	WM_P	3.920446664	144.67	14.26	41.66	11.46	30.2	18.26	10.64	246

B1	Ni	4.674677052	120.79	11.35	32.22	19.97	12.25	13.83	10.498	174
B2	Ni	4.453152079	120.4	16.42	55.9	21.51	34.39	-2.81	10.337	180
B3	Ni	4.747701736	113.49	42.13	49.29	25.12	24.17	-23.74	10.539	220
B4	Ni	5.210271678	142.47	16.46	28.96	19.97	8.99	27.8	9.638	188
B1	B	3.961610765	111.22	20.92	44.04	14.11	29.93	13.67	10.692	268
B2	B	4.249806051	103.46	33.36	58.29	20.48	37.81	6.24	11.298	252
B3	B	3.66548063433333	118.35	24.28	49.9166666666667	15.9566666666667	33.96	17.4333333333333	11.0266666666667	244
B4	B	2.785025087	140.37	18.56	47.42	13.28	34.14	32.39	11.09	260
B1	C	NA	NA	132.14	144.42	12.24	132.18	NA	10.247	254
B2	C	NA	NA	136.82	115.69	20.45	95.24	NA	11.736	246
B3	C	NA	NA	155.62	146.09	38.06	108.03	NA	11.722	254
B4	C	NA	NA	158.93	97.13	16.83	80.3	NA	11.407	260
B1	CoV_PV_EC	2.421242981	52.39	79.75	105.41	48.38	57.03	13.46	11.585	188
B2	CoV_PV_EC	2.394762998	86.71	50.11	80.78	77.83	2.95	-10.17	11.612	230
B3	CoV_PV_EC	1.887010309	86.82	68.8	71.13	14.59	56.54	7.24	11.324	250
B4	CoV_PV_EC	1.554979637	107.02	51.91	79.86	15.41	64.45	20.39	11.392	224

Appendix 9- CCFE dataset 2015-2016

Block	CC	Biomass	NO3_uptake	NO3_2	NO3_3	NO3_4	NO3_leached	NH4_uptake	WW yield
B1	WO_CoV	2.329	91.64	19.93	62.35	7.31	55.04	0.28	8.965

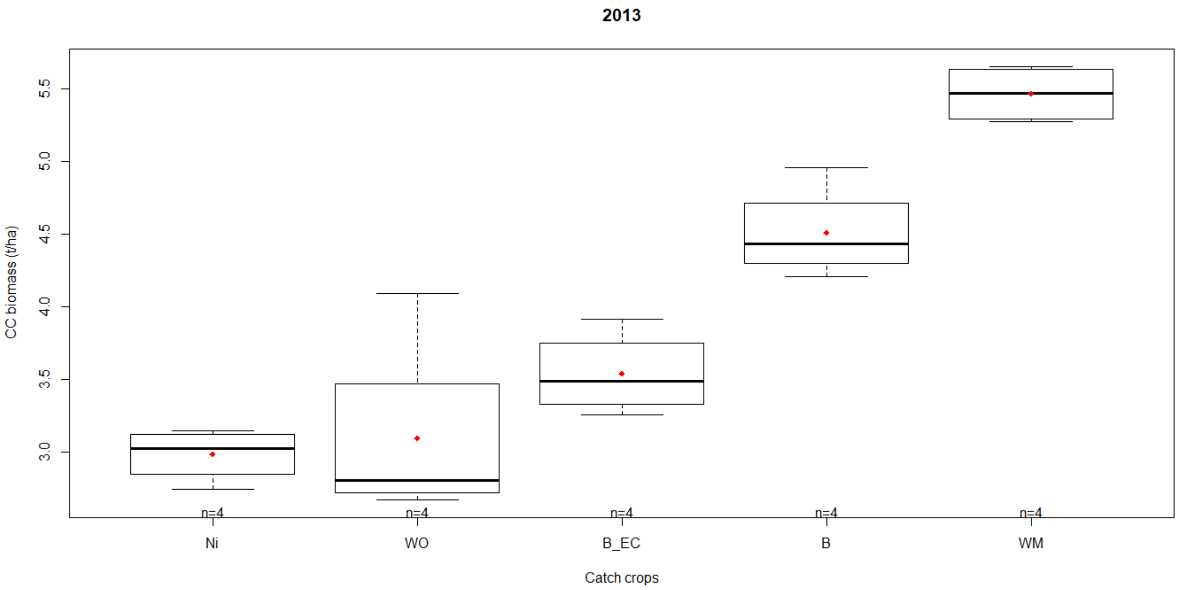
B2	WO_CoV	2.466	80.61	21.32	106.14	7.65	98.49	-5.42	9.277
B3	WO_CoV	2.859	75.5	27.21	86	5.16	80.84	-2.15	8.938
B4	WO_CoV	2.258	84.83	40.42	52.15	6.4	45.75	0.48	8.905
B1	LO_EC	1.776505231	83.85	27.72	83.32	10.33	72.99	2.01	8.809
B2	LO_EC	2.260432486	56.99	44.94	86.31	6.2	80.11	-3.82	9.267
B3	LO_EC	2.032902848	68.03	34.68	68.81	7.07	61.74	0.68	9.224
B4	LO_EC	1.077128555	85.91	39.34	117.07	5.93	111.14	1.89	8.982
B1	WM_P	2.521	103.41	8.16	53.46	6.23	47.23	-0.39	8.81
B2	WM_P	2.713	84.85	17.08	58.64	7.16	51.48	-1.18	9.299
B3	WM_P	2.416	90.62	12.09	39.18	6.05	33.13	-0.4	9.235
B4	WM_P	2.813	117.93	7.32	57.45	5.9	51.55	0.86	9.364
B1	C	NA	NA	111.57	104.88	6.44	98.44	NA	9.013
B2	C	NA	NA	101.93	58.87	9.94	48.93	NA	9.471
B3	C	NA	NA	102.71	41.03	5.57	35.46	NA	9.116
B4	C	NA	NA	125.25	106.31	6.55	99.76	NA	9.125
B1	Biomax	3.041	99.95	10.53	41.81	14.36	27.45	-1.91	8.64236524247341
B2	Biomax	2.891	84.09	20.56	52.36	14.13	38.23	-2.95	8.51365015166835

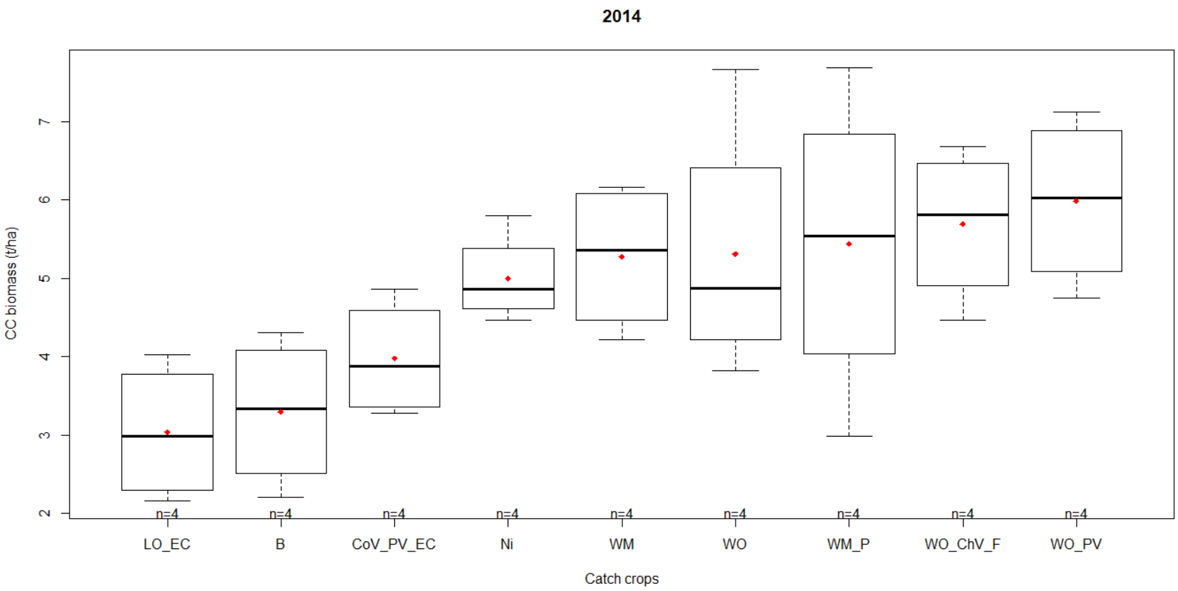
Appendix 10- CCFE dataset 2016-2017

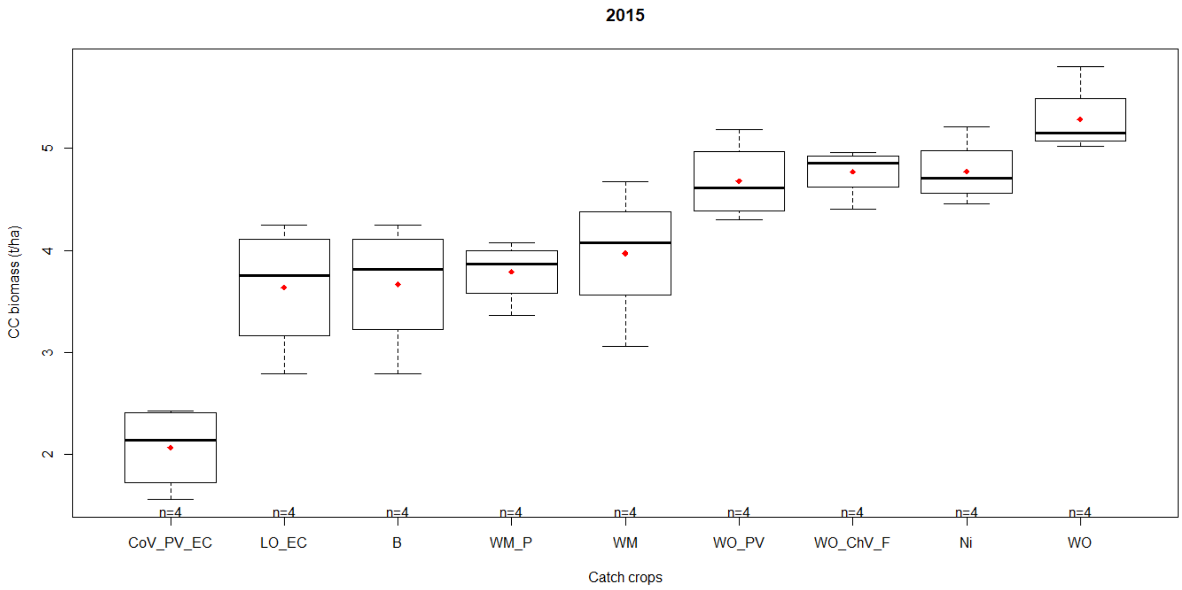
Bloc	CC	Biomass	NO3_uptake	NO3_2	NO3_3	NO3_4	NO3_leached	NH4_uptake	Yield
B1	WO_CoV	2.586963146	NA	10.2	52.92	30.52	22.4	NA	NA
B2	WO_CoV	2.731077713	NA	20.66	50.62	40.95	9.66999999999999	NA	NA
B3	WO_CoV	3.114185368	NA	41.64	74.51	28.4	46.11	NA	NA
B4	WO_CoV	2.305394057	NA	15.98	57.46	30.19	27.27	NA	NA
B1	LO_EC	2.731145059	NA	NA	64.6	50.78	13.82	NA	NA
B2	LO_EC	3.387425849	NA	31.4	81.38	57.82	23.56	NA	NA
B3	LO_EC	3.002387574	NA	12.44	109.68	43.18	66.5	NA	NA
B4	LO_EC	2.935355939	NA	15.84	80.04	54.46	25.58	NA	NA
B1	WM_P	4.979330474	NA	5.29	17.8	18.28	-0.48	NA	NA
B2	WM_P	4.510042865	NA	8.06	27.46	21.93	5.53	NA	NA

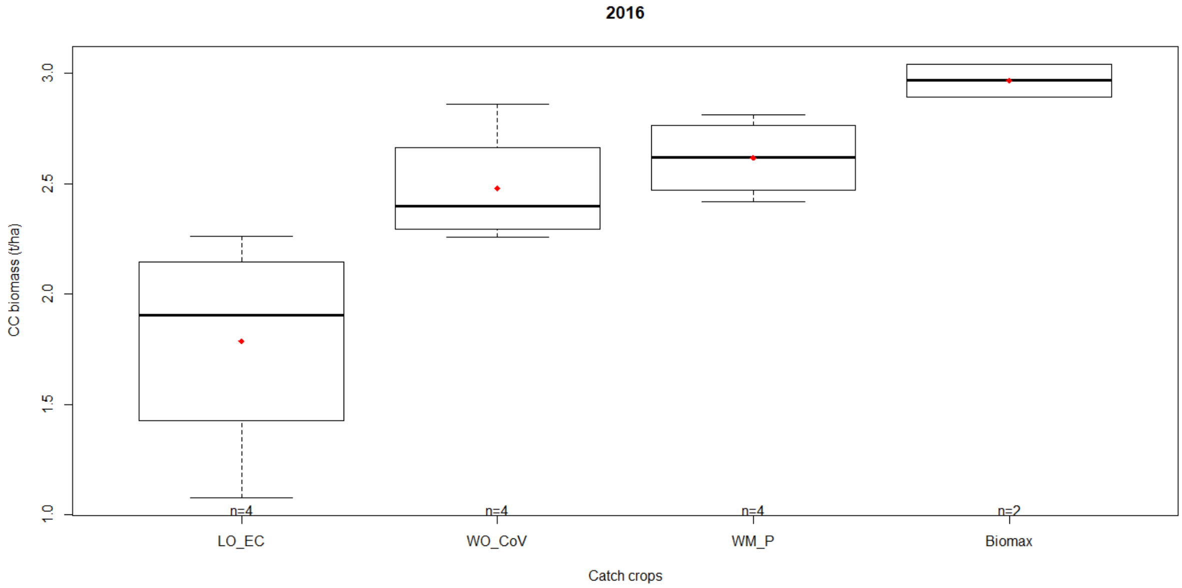
B3	WM_P	4.775906723	NA	3.88	31.03	47.33	-16.3		NA	NA
B4	WM_P	5.433040936	NA	6.38	21.67	11.78	9.89		NA	NA
B1	C	NA	NA	164.07	151.04	65.63	85.41		NA	NA
B2	C	NA	NA	143.37	221.93	62.68	159.25		NA	NA
B3	C	NA	NA	58.27	173.16	91.28	81.88		NA	NA
B4	C	NA	NA	124.71	128.9	76.67	52.23		NA	NA
B1	Biomax	7.144	NA	4.78	21.97	20.97		1	NA	NA
B2	Biomax	6.408	NA	7.64	20.69	22.42	-1.73		NA	NA

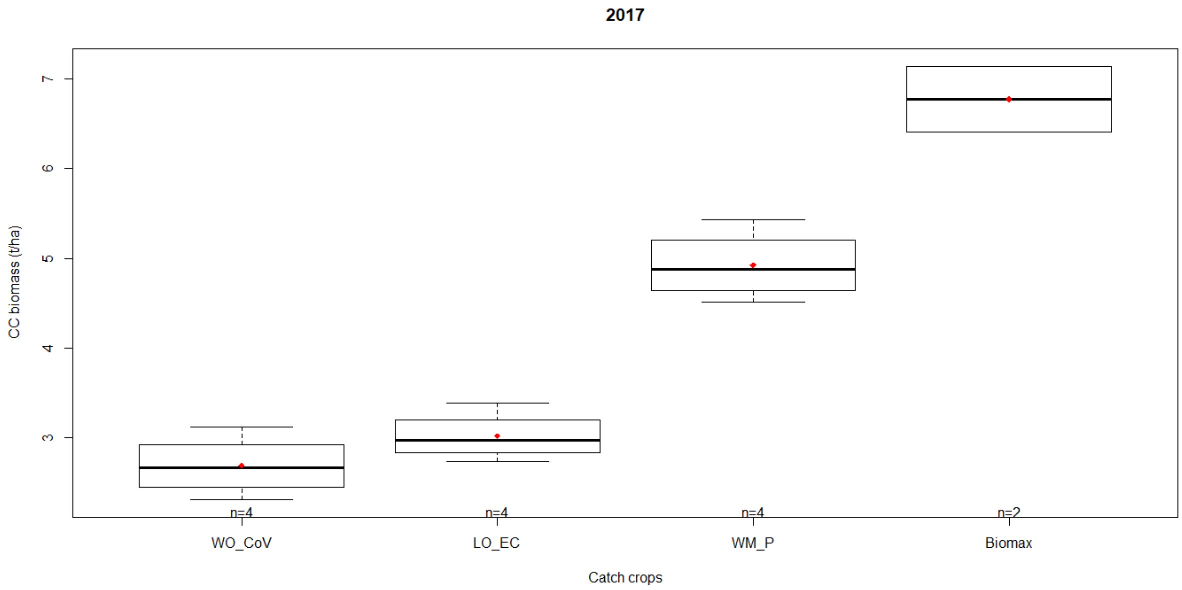
Appendix 11- CC biomass per CC and per year



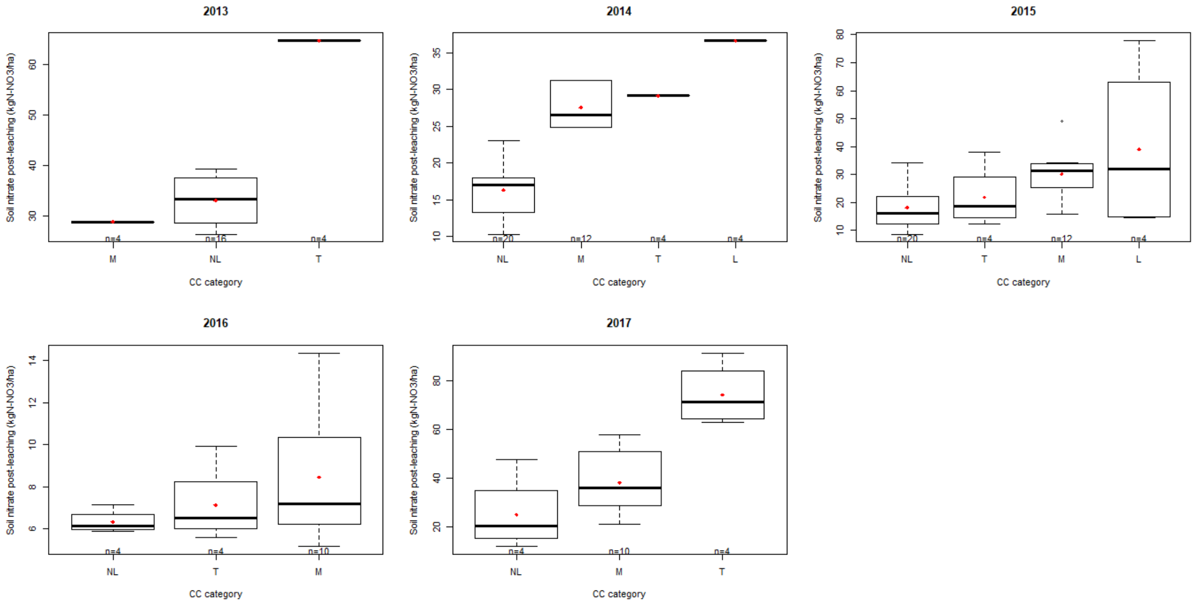



2015
CC biomass (t/ha)
2
3
4
5
n=4
CoV_PV_EC
LO_EC
B
WM_P
WM
WO_PV
WO_ChV_F
Ni
WO
Catch crops

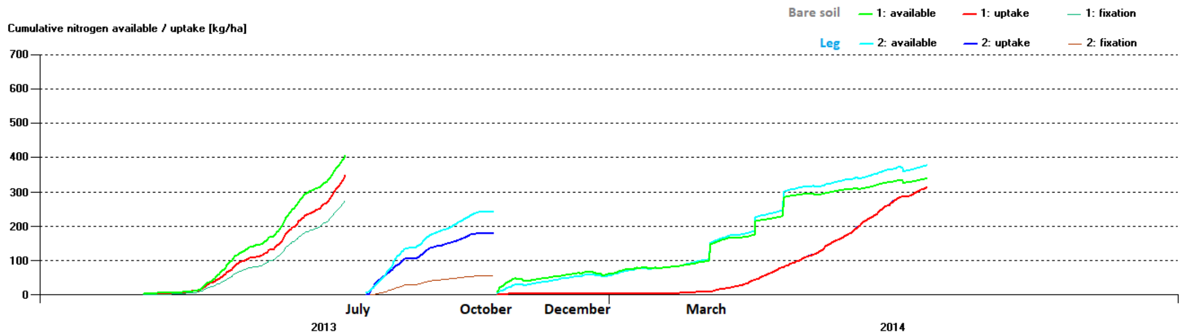

2016
CC biomass (t/ha)
1.0
1.5
2.0
2.5
3.0
n=4
n=2
LO_EC
WO_CoV
WM_P
Biomax
Catch crops


2017
CC biomass (t/ha)
3
4
5
6
7
n=4
n=4
n=4
n=2
WO_CoV
LO_EC
WM_P
Biomax
Catch crops

Appendix 12- Soil nitrate content post-leaching per CC and per year



Appendix 13- Comparison of cumulative N available and N uptake between bare soil and Leg CC with NDICEA



Appendix 14- Plot of WW yield function of CC nitrogen uptake indicator