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Agroecological service crop termination with a roller-crimper in organic vegetable systems: a good alternative to conventional soil tillage?

GEORGEL Florian
European Master of Agroecology

Abstract

Weed control and soil fertility are the two-main issues of organic production systems, especially in vegetable systems which are characterized by intensive soil tillage and irrigation, often using plastic mulches. Agroecological service crops (ASC) rolled with a roller-crimper seems a promising and more sustainable technique to cope with these issues. However, this technique is not well known and more research is needed. Thus, the GRAB in Avignon started a field experimentation in 2014, within the European SoilVeg project, to test different ASC mixtures combined with different termination techniques. This master thesis was done during the last year of the experiment, addressing the problematic: “Is rolled winter agroecological service crop technology combined with strip tillage a good alternative to conventional tillage for organic outdoor organic vegetable production for weed control and soil fertility improvement?

The field experiment based at GRAB tested two ASC mixtures (1: rye+pea and 2: barley+fababean+pea) and two ASC termination strategies (mow and incorporate ASC with soil tillage (GM) and roll ASC (RC)) effect on butternut squash agronomical performances. The experimental design was a complete block design with two blocks. 18 parameters were measured that were fit into five categories: agronomical performances, weed control, soil quality and fertility, environment and economical profitability.

The rolling technique to properly terminate an ASC is feasible, even in organic farming conditions without any herbicide. RC technique was a good alternative compared to conventional management systems (GM or no ASC) for weed control. However, it did not improve soil structure and quality on the short term. Soil was more compacted with a lower porosity than tilled soils. Squash roots were shallower on RC modalities. Squash agronomical performances were lower on RC modalities (yield was 21.7 Mg ha^{-1} for RC2 versus 34.7 Mg ha^{-1} for GM2), impacting strongly the economic performance which was also lower.

Thus, the technique of rolled winter ASC did not appear as a good alternative to conventional systems with the agronomical choices made (ASC choice, crop fertilisation, weeding management, etc.) within pedoclimatic conditions of the experiment on short term. Redoing this research without soil tillage on a long-term experiment (> 4 years) would be interesting to study if the soil quality and fertility improve with RC management.

Résumé

Les principaux problèmes en agriculture biologique sont la gestion des adventices et la fertilité des sols, particulièrement pour le maraîchage qui est caractérisé par un travail intensif du sol et une forte irrigation, ainsi que l’utilisation courante de paillages plastiques. Le roulage de couverts végétaux avec un rouleau crêpeur semble être une technique prometteuse pour répondre de façon durable à ces problèmes. Mais peu connue, cette technique demande plus de recherche. C’est pourquoi le GRAB d’Avignon réalise des essais depuis 2014 au sein du projet Européen SoilVeg, qui teste différents couverts végétaux et techniques de destructions. Ce mémoire de fin d’étude a été réalisé pendant la dernière année du projet. La problématique de recherche est la suivante : « Les couverts végétaux d’hiver roulés sont-ils une bonne alternative aux systèmes de travail du sol conventionnels pour la production maraîchère biologique de plein champ pour l’amélioration de la gestion des adventices et de la fertilité du sol ? »

Basé au GRAB, l’essai teste l’effet de deux couverts végétaux (1 : seigle+pois et 2 : orge+féverole+pois) combinés à deux méthodes de destruction du couvert (broyage et enfouissement du couvert (GM) et roulage du couvert (RC)) sur les performances agronomiques de la culture de courge butternut. Le dispositif expérimental comporte deux

blocs complets. 18 paramètres ont été mesurés pour répondre à cinq catégories d'indicateurs : performances agronomiques, gestion des adventices, qualité et fertilité du sol, environnement et rentabilité économique.

Le couchage d'un couvert est réalisable, même en agriculture biologique sans utilisation d'herbicide. La technique RC est une bonne alternative comparée aux systèmes de travail du sol conventionnels (GM ou absence de couvert) pour la gestion des adventices. Cependant, la structure et la qualité du sol n'ont pas été améliorées sur le court terme. L'enracinement des courges était plus superficiel sur les modalités RC. Les performances agronomiques des courges étaient moins bonnes sur les modalités RC (rendement de 21.7 Mg ha^{-1} pour RC2 et 34.7 Mg ha^{-1} pour GM2), impactant fortement la rentabilité économique qui était très inférieure.

Ainsi, à court terme la technique des couverts d'hiver roulés ne semble pas être une bonne alternative aux systèmes avec travail du sol dans les conditions agronomiques et pédoclimatiques choisies. Refaire cette expérimentation sans travail du sol sur le long terme (> 4 ans) serait intéressant pour voir si la qualité et la fertilité du sol s'améliorent avec le temps sur RC.

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Abbreviations

ASC: Agroecological Service Crops. It identifies crops with multiple agro-environmental functions and refers to many terms as catch crops, complementary crops, living mulches, etc.

ANOVA: Analysis of variance

B.H.: Benjamini & Hochberg (adjustment method of p-value in statistical analysis)

CIRAME: Centre d'Information Régional Agro-Météorologique (Regional Information Center of Agrometeorology)

Control ST: Control plot with soil tillage limited to the transplantation line with a strip-till

Control W: Control plot with tilled soil

CST: Control ST

CW: Control W

CTIFL: Centre Technique Interprofessionnel des Fruits et des Légumes (Technical center for fruit and vegetable production)

C:N ratio: carbon-to-nitrogen ratio

EPLEFPA : Etablissement Public Local d'Enseignement et de la formation Professionnelle Agricole les sillons de Haute Alsace (public agricultural secondary school in Haute Alsace)

GHG: GreenHouse Gases

GM: Plot with an ASC terminated into Green Manure (ASC chopped and incorporated into the soil with tillage)

GRAB: Groupe de Recherche en Agriculture Biologique (Research group in organic agriculture)

ha: hectare

INRA: Institut National de Recherche en Agronomie (French National Institute for Agricultural Research)

kPa: kiloPascal

LSD test: Least Significant Difference test (method for comparing factor levels means after the ANOVA null hypothesis of equal means has been rejected using the ANOVA Fisher's test)

Mg: Megagram (one megagram is equal to one tonne)

N: nitrogen

NO_2^-: Nitrite

NO_3^-: Nitrate

p.adjust: Adjusted P value (for statistical analysis)

RC: Plot with an ASC terminated with a Roller-Crimper

s.e.: standard error

SMIC: Salaire Minimum Interprofessionnel de croissance (index-linked guaranteed minimum wage) spp.: species

sqrt: square root

UAA: Utilised Agricultural Area

vs.: versus

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1. Introduction

Conservation agriculture is characterized by no or minimal soil tillage, to preserve soil characteristics such as structure, composition (nutrients and organic matter, water, air/gases and organisms) and biodiversity (FAO, 2008). Already greatly studied in cereals fields, research on conservation agriculture in vegetable systems is scarce, especially in organic farming.

The management of cover crops is one of the key elements of conservation agriculture, especially in organic farming because of the ban on synthetic herbicides and to a lower extent of synthetic fertilizers.

In conservation agriculture systems, cover crops have many benefits and purposes such as: reduce erosion, add organic matter to the soil, improve the soil structure, fix atmospheric nitrogen (when legumes are included) and limit nitrogen leaching, increase soil productivity, maintain moisture and improve weed control (Hartwig & Ammon, 2002).

Cover crops can be combined with no-till systems to decrease erosion and maintain the above-mentioned soil characteristics (Kassam et al., 2009). Besides these benefits, this technique aims also to reduce other inputs such as plastic mulch, fossil fuels and organic fertilizers.

On this basis, the "*Groupe de Recherche en Agriculture Biologique*" (GRAB) began experiments three years ago to test cover crops associated with two different destruction techniques ([1] roller crimping or [2] mowing and incorporation into soil) to assess these technique performance. GRAB is a small organic research centre located in Avignon (South-East France). Created in 1979, it aims to improve organic practices and production techniques of fruits and vegetables, as well as favour knowledge and innovation dissemination.

With this research on rolled cover crops, GRAB takes part of the European project "SoilVeg" [1], which aims to improve the management of Agroecological Service Crops (ASC)[2], in the network European Coordination of European Transnational Research in Organic Food and Farming Systems (CORE Organic Plus).

"SoilVeg" project gathers 14 partners in 9 different countries across Europe during three years (2015-2017). Each country studies different crop mixtures and crop termination strategies effects on subsequent crop, weeds, pest and disease occurrence, nutrient losses, greenhouses gas emissions. It aims to evaluate the effect of the roller-crimper technology on cash crop yield and quality, soil quality and fertility, weeds development, fossil fuel consumption and pest and disease occurrence.

This Master Thesis was done during the last year of the project, continuing the experiment on the use of autumn/winter cover crops, including its termination, to assess the performance of the technique on an organic squash crop.

The main question this work study seeks to answer is: "Is rolled winter ASC technology combined with strip tillage a good alternative to conventional tillage for organic outdoor organic vegetable production, specifically for weed control and soil fertility improvement?". This

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[1] For more information on "SoilVeg" project: http://coreorganicplus.org/research-projects/soilveg/.

[2] ASC: identifies crops with multiple agro-environmental functions and refers to many terms as catch crops, complementary crops, living mulches, etc.

question was divided into five hypotheses related to the topics of agronomical performance, weed control, soil fertility, environment and economic profitability.

The second chapter of this report is presenting the background information on this research. It first describes the issues of organic vegetable production (weed control and soil quality and fertility management). Then the benefits of ASC are described. Eventually, a review on the roller-crimper technology is done. Chapter three presents the material and methods used for this research. The main results of the experiment are detailed in chapter four. These results are discussed in chapter five. Chapter six is a conclusion of this report supported by prospects.

2. Rolled cover crop technique for organic vegetable farming

2.1. Organic vegetable production: specificities and issues

Organic agriculture aims to sustain the agroecosystem health, including soils, biodiversity and people (IFOAM, 2005). Organic cropping practices are based on agronomic, biological and mechanical methods, without any use of synthetic fertilizers or pesticides (FAO, 1999). Consequently, weeds and soil fertility (soil biological quality, soil structure and soil organic matter) management are the main issues in organic systems (Peigné et al., 2007).

Organic vegetable systems are especially concerned with these two issues compared to cereal fields. This can be explained by the agronomic specificities of vegetable production regarding soil fertility and weed management.

2.1.1. Soil fertility management

Vegetable fields often require a thin soil tillage and have a fast cropping rotation (around 1.5 crop per year) which lead to a high number of machinery passages, often correlated with soil compaction (Jokela and Nair, 2016).

Besides, nearly all the vegetable crops are irrigated in southern France, either with drip or sprinkler irrigation since the vegetable crops require a high amount of water for short periods. Water application increases nutrient mineralisation and weed growth where the water is applied.

Vegetable production requires the use of fertilizers because crops have a high nutrient need during short time periods. Because chemical fertilizers are not allowed in organic farming; organic vegetable growers could have trouble finding to find organic fertilizers for their crops. As a result, organic vegetable fields receive generally more organic matter and green manure than non-organic fields and no chemical fertilizers (Peigné et al., 2015; Védie and Métais, 2013). In southern France, most of the organic vegetable farms do not have any animals in their production system and thus, need to import fertilizers and amendments (Peigné et al., 2015). However, it is not always possible to find animal manure, especially in the Provence Alpes Cote d'Azur region (see Figure 3 on page 18) where animal manure is missing due to lack of livestock farms. Furthermore, farmers usually do not have the proper material to spread animal manure or compost, only having a fertilizer sprayer, especially for small vegetable producers. Thus, fertilisation represents a high expense for organic vegetable growers.

2.1.2. Weed control

The main solution for weed control is the mechanical destruction, but it is only feasible at an early stage of crop growth. Another solution to prevent weed development is to cover soil with plastic mulch (Butler et al., 2016) (e.g. on Picture 1).

Plasticulture has many advantages for vegetable growers, especially in organic agriculture, since a plastic layers prevents weed growth (Feeser et al., 2014), retains soil moisture and increases soil temperature (+2.7 °C at 5.08 cm soil depth compared to a bare soil) allowing an early planting and shorter crop growth cycle (Lamont, 2005). But plastic mulch also has disadvantages. It needs to be bought and settled, creating labour and investment costs. It uses a non-renewable source (petroleum) and is not recyclable. It can increase run-off and erosion because soil becomes impermeable (Feeser et al., 2014). Biodegradable mulches represent an improvement from an ecological point of view, but sometimes have decomposition problems.

Picture 1: Eggplant (*Solanum melongena*) on black plastic mulch in greenhouse (GRAB, 17/04/2017)

In outdoor vegetable production, plastic mulches are mostly used on small fields on diversified vegetable farms. They are not commonly used on big vegetable fields which are managed as cereal fields, because vegetable growers cannot afford to buy such material. Thus, they often rely on chemical herbicides to control weeds or mechanical weeding in organic farming.

Therefore, more sustainable and efficient management techniques for weed control and soil fertility are necessary to provide new tools for growers to cope with these issues. The use of cover crops seems to be a promising technique, which adds organic matter to the soil and has a weed suppressive effect.

2.2. Agroecological Service Crops (ASC)

“Cover crop” could be an ambiguous term since it names many different crops with different purposes and does not embrace all the non-harvested crops in a field. Therefore, Canali et al. (2013) introduced the term of “Agroecological Service Crops” (ASC) which identifies crops with multiple agro-environmental functions (Table 1) and refers to many terms as catch crops, complementary crops, living mulches, etc. (see Appendix 1). This terminology will be used in this thesis as the “ASC” term is also used in the European SoilVeg project in which GRAB is involved.

Table 1: ASC agro-environmental functions and characteristics

ASC agroecological functions	ASC characteristic and management
Improve soil fertility	The ASC can be used as green manure to add organic matter into soil. High ASC biomass production is needed. If the objective is to provide sufficient nitrogen for the subsequent crop, leguminous species can be favoured in order to increase available nitrogen in the system. In this case, the ASC residues should have a low C:N ratio (at least lower than 35) to avoid nitrogen shortage via nitrogen immobilisation by microorganisms to mineralize organic matter. The residues can be incorporated then into the soil to increase its decomposition.
Protect soil against erosion and runoff	The ASC should establish quickly and have a strong rooting system. It should then provide a good soil coverage.
Reduce nutrient leaching	ASC can be used as nutrient buffer. Cover crop can scavenge residual N, using for example grasses species that have a high need in N.
Decrease weed occurrence	The ASC need to compete strongly weeds. It must establish quickly, have a high density of foliage to avoid light transmittance and compete for nutrient. The cover crop can be selected depending on its allelopathic potential. Residues of the cover crop can be laid as a mulch to reduce weed germination.
Manage diseases and pests	ASC can "break" the crop rotation when a plant from a different family is used. Plant species that repulse pests and that cannot be host of diseases can be used. ASC producing flowers on a long-time period can provide food for beneficial insects (pollen and nectar) for biological control.
Increase biodiversity	Use a diverse mixture of species and families. Try to promote flowers.

2.2.1. ASC: an essential tool for organic production

ASC have many benefits and purposes that are usually related to soil fertility management, weed control, pests and diseases.

- **Soil fertility management**

Soil erosion, temperature and humidity. The main benefit on soil is to reduce water and/or wind soil erosion and water runoff (Hartwig and Ammon, 2002) during ASC cultivation. This benefit is particularly important in slopes exposed to high rainfall and strong wind, especially when ASC is implanted when soil is more susceptible to erosion (often late autumn and winter). This could improve water quality, reduce nutrient runoff and leaching, and sedimentation in the rivers (Baldwin and Creamer, 2006).

When the ASC is maintained on the soil surface, it helps to conserve soil moisture, reduce evaporation, increase water infiltration and water holding capacity (Baldwin and Creamer, 2006). It also reduces topsoil temperature.

Soil organic matter, microorganisms and nutrients. ASC helps to build a more fertile soil by adding organic matter into soil, resulting in carbon sequestration, and improving soil structure (Dabney et al., 2001). Soil microorganisms and earthworms are stimulated and contribute to enhance nutrient cycling. Deep rooting ASC can help to increase deep porosity.

ASC has an impact on nitrogen availability for the subsequent crop. If ASC includes legumes, it can fix atmospheric nitrogen that will be available for the succeeding crop after ASC residues breakdown (Hartwig and Ammon, 2002). Also, non-legumes ASC can scavenge residual NO_3^- -nitrogen, avoiding nutrient leaching or runoff (Dabney et al., 2001). If well synchronized, the nitrogen released from ASC decomposition can coincide with the cash crop nutrient uptake. This release depends on many factors such as ASC species, growth stage, climate or ASC destruction technique. The mineralisation rate is generally assessed by the C:N ratio of the ASC residues. It is considered that C:N ratio greater than 35 causes N immobilisation, leading to late N availability for the subsequent crop (Dabney et al., 2001). Cereals often have often high C:N ratio (> 35), whereas it is often lower than 20 for legumes, releasing N for subsequent crop faster.

An ASC can also increase mycorrhizal fungi activity in the soil, benefiting the ASC and cash crop with a higher water and nutrient availability resulting from the symbiotic relationship between the mycorrhiza and the plant roots (Dabney et al., 2001).

- ### Weed control

During ASC cycle, weeds can be controlled by ASC which smothers and shades weeds, reducing light transmittance. It also outcompetes weeds for nutrient and water (Baldwin and Creamer, 2006). Another factor that can act is the production of allelopathic compounds which are toxic for the seeds to germinate. The amount and efficiency of this production depends greatly on the ASC species.

When ASC residues are left on the soil surface after termination, they can reduce weed emergence during the subsequent cash crop.

- ### Pest and diseases

ASC have an impact on diseases and pest, which can be positive, negative or neutral. On one side, it can host soil-borne diseases and harmful insects, whereas on the other side it can increase biological control (Baldwin and Creamer, 2006). ASC allows producers to increase the number of crop and species in their crop rotation, being able to add a new crop family or species while reducing the pest and disease risks.

- ### Other benefits

It is recognized that ASC increases biodiversity (abundance of species and richness/diversity) at many scales, from the soil microorganisms to the birds, including also the plant species in the cover crop and the insects (Overstreet et al., 2010). It will also provide food for the pollinators which are attracted by the flowers of the cover crops (vetch, pea and fababean are very good examples) and the beneficial insects which could reduce the amount of pests and diseases (Jackson and Harrison, 2008).

It can be also taken into account the maintenance of the landscape beauty (SoCo Project Team, 2009).

2.2.2. Which ASC should be preferred?

Many studies were carried out to find the best cover crop species or mixtures in different environments. The following characteristics are often required (OSCAR project team, 2016; Pousset, 2000):

- A rapid germination and growth to quickly compete weeds,
- Low price of ASC seeds,
- A late seed formation and maturity to avoid the production of viable seeds before cover crop termination,
- A powerful rooting system to improve soil structure and soil nutrient uptake,
- A high competition potential against weeds (Creamer et al., 1997),
- A high biomass production with a high density and a homogenous production and soil coverage (Buchanan et al., 2016),
- Easy termination with low regrowth potential,
- Fit with the off season between two cash crops.

ASC choice depends on the intended objective. It can be used as green manure, nutrient scavenging crop, nitrogen fixing crop or banker crops, etc. Thus, different ASC agro-environmental functions can be pursued, as shown previously in the Table 1.

ASC species are usually from three main plant families: *Brassicaceae*, *Fabaceae* and *Poaceae*. Other specific plants can also be used such as *Phacelia* spp., *Fagopyrum* spp., *Linum usitatissimum* or *Helianthus* spp.. Brassicaceae family is not commonly chosen as ASC for vegetable production since many cultivated crops are from the same family (e.g. turnip, cabbages, arugula or radish).

As mentioned in part 2.2.1., legumes and cereals ASC are often distinguished in literature. Legumes are used to fix nitrogen that will be quickly available for the subsequent crop. But legumes are not always good competitors against weeds. Besides, legumes are less efficient to scavenge soil N and fix a lower amount of atmospheric N if there is a high amount of available N (White et al., 2016). A mixture of them is often suggested in order to combine the benefits of both plant families (Price and Norsworthy, 2013). Adding cereal grains in the mixture has many advantages. They are producing a high biomass, can support hard winter, provide a good erosion control and are good nutrient scavengers, especially for nitrogen. They are also strong competitors against weeds especially in autumn by mechanical and allopathic means. In addition, Poaceae straw is very slow to decompose due to its high content in cellulose, providing a long-lasting soil mulch coverage. Moreover, it diversifies the crop rotation since the Gramineae family is not cultivated in vegetable systems.

2.2.3. ASC termination techniques and soil tillage

The management of ASC is one of the key elements of conservation agriculture, especially in organic farming because of the ban of synthetic herbicides and synthetic fertilizers (Carr et al., 2012). Organic farmers can only rely on ASC mechanical termination or livestock grazing. Different mechanical termination methods exist: the ASC can be (1) mowed using a flail mower or a mower with hammers, (2) cut with an undercutter or a sickle/rotary mower, (3) rolled with a roller-crimper or a cultipacker or a simple roller, (4) shaded with a black plastic layer, or (5) directly incorporated into the soil through soil tillage (Feeser et al., 2014) (see Pictures on Figure 1).

	**(1) Mowing** GRAB 18/04/2017	 	**(4) Covering with black plastic** GRAB 23/06/2015
	**(2) Undercutting** Photo by Joanne Thiessen Martens[3]		
	**(3) Roller crimping** GRAB 19/04/2017		**(5) Soil tillage** Photo by Reed Hamilton[4]

Figure 1: Pictures of ASC termination means

Among the techniques proposed to terminate ASC in organic farming, flail mowing (1) followed by incorporation into the soil as green manure is the most frequently used (Canali et al., 2015). The cover crop is shredded in small pieces that degrade quickly and persist less as a mulch compared to mowed or rolled cover crop (Wayman et al., 2015). It includes soil tillage after ASC shredding in order to speed up its breakdown in the soil and nitrogen release to the crop (Dabney et al., 2001; Wortman et al., 2012).

The "Green Manure" management induces soil disturbance with the drawbacks mentioned previously and exposes soil surface to erosion before the subsequent crop transplantation or sowing (Kornecki, 2016). Also, ASC as green manure do not provide a great protection against weeds during the cash crop cultivation, unless the ASC has allelopathic properties, often requiring the use of plastic mulch or frequent mechanical weeding. Thus, the roller-crimper technique seems to be a very promising technique to conserve soil and control weeds.

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[3] Retrieved from: http://www.pivotandgrow.com/resources/production/green-manures/module-3-managing-green-manures/#1467151887517-e674df54-5dbf (Accessed 21/06/17)

[4] Retrieved from: http://grassvalleygrains.com/2011/05/ (Accessed 21/06/17)

2.3. Roller-crimper ASC termination

Roller-crimper termination kills the cover crop by breaking or crushing the stems of plant at several places (Picture 2), leading to cover crop desiccation (Balkcom et al., 2007). The blades around the roller damage the vascular plant systems without cutting the plant, to avoid cover crop re-sprout (Baldwin and Creamer, 2006). According to Ashford and Reeves (2003), it may have the same efficiency as chemical herbicide termination if done properly.

Picture 2: Rolled barley stem (GRAB)

Three main conditions are required for a proper ASC termination: use the proper termination tool, select the adapted ASC species, the variety, and having a good timing for ASC termination.

2.3.1. Machinery and practical use

Three main different roller-crimper types can be distinguished depending on the blade shapes: straight blades, short-staggered straight blades and spiral blades (Figure 2). The term “roller-crimper” (RC) will be preferred in this report since it is the most widely spread within English scientific literature (Appendix 1). Raper et al. (2004) tested different roller-crimper pressures and shapes to terminate the cover crop. They found that there were no differences for these factors on the crop termination efficiency, but that spiral blades and short-staggered straight blades could reduce significantly vibrations of the roller compared to strait blades. Later, Kornecki et al. (2009) did not find any influence of rolling speed in rye cover crop mortality.

Figure 2: Different roller-crimper’s blade type (from the left to the right: straight blades[5], short-staggered straight blades[6] and spiral blades[7])

This technique originated in South America in the late 1970’s, where it was used in cotton or soybean fields (Derpsch, 2001). Research has developed during the last 20 years in the US and Canada, for field crops (mostly soybean and cotton), and later for outdoor vegetable production (Ashford and Reeves, 2003; Butler et al., 2016; Carr et al., 2012; Delate et al., 2012;

[5] Retrieved from: http://www.metalurgicagloria.com.br/site/ (Accessed 19/07/17)
[6] Source: GRAB roller-crimper
[7] Source: Estonian Crop Research Institute (ECRI) roller-crimper

Halde et al., 2015; Jokela and Nair, 2016; Kornecki et al., 2009; Luna et al., 2012; Tillman et al., 2015). European researchers started to assess the feasibility of this technique more recently for vegetable production (Atelier Paysan, 2016; Canali et al., 2015, 2013; Montemurro et al., 2013) since conservation agriculture is less widespread in Europe than America (Carr et al., 2012; Triplett and Dick, 2008).

According to Peigné et al. (2015), only 2% of the European organic farmers practicing conservation agriculture and using cover crops were rolling these cover crops. Also, these 2% were probably not vegetable growers. In South of France, Védie and Métais (2013) found that among the 29 organic vegetable growers interviewed, none were using rolled cover crops. Thus, this technology requires more studies and implementation to fit with the European climatic conditions.

After rolling the cover crop, two methods exist to plant the subsequent crop. The first one is to sow or transplant the cash crop directly into the soil through the mulch layer. The second technique is to till the soil on a narrow strip to increase local mineralisation and facilitate seeding or plantation. Strip till can be combined with a planting machine or seeding machine.

Strip tillage is more used in Europe compared to US (Carr et al., 2012). Strip tillage must be done in the same orientation and direction than the rolling (Atelier Paysan, 2016; Reberg-Horton et al., 2012).

Thus, to assess the potential of the rolled ASC combined with strip till, the combined effects of two practices should be considered: conservation tillage (strip tillage) and the use of rolled cover crop mulches.

2.3.2. ASC for roller crimping termination

In addition to the point mentioned previously in 2.2.2., a good ASC established in autumn and killed by rolling in spring should:

- Be easily terminated by mechanical means (Creamer et al., 1997),
- Not regrow after termination either by tillering or straightening up,
- Provide sufficient nitrogen for the next crop, or at least avoid nitrogen shortage (Creamer et al., 1997)
- Last a long time on soil as mulch to suppress weeds after ASC termination.

Also, the field should not be contaminated with too much weeds, especially perennials (e.g., rumex spp. and quackgrass) since the roller-crimper will not kill them (Atelier Paysan, 2016).

Another important factor is the selection of the right variety for each species. For instance, Reberg-Horton et al. (2012) found that depending on the variety, rye has produced between 8.6 and 11.5 Mg ha^{-1} of dry biomass in monocropping. Also, flowering time can change depending on the earliness of each variety, which influences the possibility to effectively terminate the ASC at the right time.

It is generally accepted that a mixture of different ASC species is a good option to combine the different ASC advantages. For ASC termination, it implies that all the species and varieties mixed reach the right phenological stage at the same time for an effective termination.

2.3.3. ASC mixtures

One of the key points to succeed ASC termination is to choose the right cover crop mixture with the right species and varieties, but it is not easy since research on ASC is lacking for vegetable production. In Table 2, a selection of species that could be used as ASC to be terminated with the roller-crimper in northern climates is listed. Among these species, a combination of rye and hairy vetch seems very promising to provide high biomass, a thick mulch layer that degrades slowly and nitrogen thanks to hairy vetch (Parr et al., 2011). Many studies on rolled cover crop use either rye alone or a biculture of rye-hairy vetch (for instance: Altieri et al., 2011; Feeser et al., 2014; Jokela and Nair, 2016; Kornecki et al., 2012; Leavitt et al., 2011; Lowry and Brainard, 2016).

Other species can also be used such as common vetch (*Vicia sativa*), alfalfa (*Medicago sativa),* red clover (*Trifolium pratense*), blue lupine (*Lupinus angustifolius*), buckwheat (*Fagopyrum esculentum* Moench.), black mustard (*Brassica nigra* L.) or sorghum (*Sorghum bicolor* L.), but more research is required to establish technical references on these species (White et al., 2016).

Table 2: Selection of ASC species for a roller-crimper termination in temperate climate (Baldwin and Creamer, 2006; Parr et al., 2011; Shirtliffe and Johnson, 2012)

Plant	**Advantages**	**Inconvenient**
Legume		
crimson clover (*Trifolium incarnatum* L.)	Good shade tolerance. Relatively high biomass	Blooms 3-4 weeks before hairy vetch and field pea. High C/N ratio.
hairy vetch (*Vicia villosa* Roth.)	Dense cover, can climb if seeded with rye. Relatively high biomass	If it produces mature seeds, can be seen then as a weed. Deliver maximum N for subsequent crop in early to end of May.
field pea or Austrian winter pea (*Pisum sativum arvense* L.)	Can climb	Decompose rapidly and do not control weed enough in mulch. Maximum N peak content in early to end of May
subterranean clover (*Trifolium subteraneum* L.)		Do not produce high biomass. Develop seeds below ground in late spring. Early blooming as crimson clover.
fababean (*Vicia faba* L.)	High biomass production. Fast flowering.	Expensive seeds
Cereal		
rye (*Secale cereal* L.)	Most commonly used. Performs well mixed with vetch. Weed suppressive in a mulch. Best scavenger of excess N soil. High allelopathic potential.	
annual ryegrass (*Lolium multifolium* Lam.)	Dense root system, good protection against erosion	Can be difficult to control and then become serious weed. It requires high amount of water and nitrogen
wheat (*Triticum aestivum* L.)	Farmer can harvest grain. It provides a good overwintering ground cover	
barley (*Hordeum vulgare* L.)	Good smother crop. Early flowering.	Must be planted early to avoid winter kill.
oat (*Avena sativa* L.)	Grow well in cool climate and provide a quick soil coverage in autumn.	Should be winter killed to be effectively terminated. Thus, requires cold winters.

2.3.4. ASC termination timing

The choice of ASC variety and species earliness need to be adapted with the date of termination, which depends on the subsequent crop plantation date. Indeed, the cover crop needs to be terminated at the right time. Generally, ASC species must be rolled in an advanced flowering stage to avoid tillering or straightening up. For each species used in this study, the recommended stages are:

- Cereals need to be at the early milk stage (BBCH-scale[8] 71) to soft dough stage (BBCH-scale 85) (Ashford and Reeves, 2003),
- Vetch: when pods are first seen (BBCH 70) (Reberg-Horton et al., 2012).
- Fababean: not well studied. A termination later than late flower (BBCH' 67) seems necessary to avoid Fababean regrowth (Shirtliffe and Johnson, 2012),
- Pea: not well studied. Shirtliffe and Johnson (2012) did not find any difference of the growing stage (between early flowering stage (BBCH' 61) and late pod fill (BBCH' 76)) on the termination efficiency by a roller-crimper.

Cash crop transplantation needs to be done at least two to three weeks after rolling to restore soil moisture depleted by ASC (Altieri et al., 2011; Reberg-Horton et al., 2012).

2.3.5. Potential benefits of roller crimping technique

Additional benefits of the rolled ASC technique combined with strip till could be divided into 3 categories: agronomic, economic and environmental.

***Agronomic advantages.** It should help to solve the two main issues of organic vegetable production: weeds and soil fertility/quality management. As a tool to manage weed, the mulch originating from the rolled cover crop should deter weed growth by providing a physical barrier; intercepting the solar radiation which reduces the soil surface temperature, evaporation and light transmittance; and could have allopathic properties which directly depends on the species used in the cover crop (Altieri et al., 2011). The strip-till technique promoted soil quality. According to many authors, it should decrease soil compaction, increase soil aggregate stability, increase biological soil activity and arbuscular mycorrhizal fungi survival, increase soil carbon content and decrease nutrient losses (wash off and leaching) (Clark, 2008; OSCAR project team, 2016; Peigné et al., 2007; SoCo Project Team, 2009).

Toussaint and Ciotola (2015) recently mentioned the roller crimping technology as a tool for integrated pest management. In their study, they found that rolled cover crop reduced drastically the soil infestation by *Pseudomonas syringae,* a bacterium that affects more and more cucurbits species, against which chemical treatments are not satisfying. They also found reduction of *Cladosporium cucumerinum* when the attack was severe.

***Economic benefits.** The technique is reducing the farm external inputs use, including fertilizers, fuel and black plastic mulches in some cases (Feeser et al., 2014). It also aims to decrease labour requirements, the weeding time and number of tractor passages for soil tillage operations (Luna et al., 2012).

***Environmental benefits.** Roll an ASC should increase water quality which is especially beneficial near the water catchment areas (less erosion), increase the air quality (less wind

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[8] BBCH: system of uniform coding of phenologically similar growth stages of all mono- and di-cotyledoneous plant species, originating from German language (Bleiholder et al., 2001)

erosion and less particulate emission from fuel consumption) and decrease the greenhouse gas emissions (Clark, 2008).

2.3.6. Problems and drawbacks identified

Despite its benefits, this technique is not widespread for vegetable production throughout the world because of the potential problems. Some previous research, mostly conducted in the US, has identified key issues in the following three categories: agronomy, economy and knowledge gaps.

* **Agronomy.** The technique is often based on total herbicide use (such as glyphosate) combined with the roller-crimper to terminate completely the cover crop (SoCo Project Team, 2009). Thus, weed control seems to be still the main issue of the rolling technology since mechanical weeding is not feasible anymore during cash crop cultivation. In fact, soil tillage as a mean for weeding would damage the soil mulch coverage and increase soil disturbance (Morse, 1999; Teasdale et al., 1991). ASC re-growth after its termination can become a weed. ASC including cereals could lodge, jamming then in the strip till and not providing good soil cover (Atelier Paysan, 2016). After a proper ASC termination, the mulch created could degrade too fast and not last long enough to compete weeds effectively (Altieri et al., 2011).

The mineralization of the mulch seems to be a huge issue. This process is slower than cover crop incorporated into the soil or bare soil, because less residues are in contact with the soil (Morse, 1995; Treadwell et al., 2008). The subsequent cash crop often needs to be fertilized because the mulch layer is not providing sufficient nitrogen (Wells et al., 2013). This could explain in part an earliness loss for the subsequent cash crop (Morse, 1995). Also the cover crop mulch slows plant growth probably because it reduces soil temperature. Jokela and Nair in a recent study (2016) measured differences in soil temperature from 0.6 to 3.8 °C, between conventional destruction of cover crop (green manure) and rolled cover crop.

The cash crop often needs to be transplanted to avoid too high weed pressure (Morse, 1995). Some trials were done in France where vegetable growers tried to seed directly into the mulch, but the results were not satisfactory, the seeds did not germinate or were outcompeted by weeds (Atelier Paysan, 2016).

The mulch residues could also be toxic for the subsequent crop. For instance, Altieri et al., (2011) mentioned that farmers in South America were waiting between one and two weeks after cover crop mulch of oilseed radish or legumes and between three and four weeks after winter cereals before transplanting the cash crop to avoid this toxicity.

In some cases, the rolling technology can increase soil compaction, especially the first year of the technique with a topsoil compaction (Price and Norsworthy, 2013). But as mentioned by Peigné et al. (2007), topsoil compaction may be only temporary, occurring during the transition period between conservation tillage and conventional tillage.

Peigné et al. (2007) refer to new pest problems with a significant increase of slugs, which were favoured by the mulch humidity. This problem was recently confirmed in a report of Fiedler (2016) in France. Also, Hummel et al. (2002) found more suckling insects such as aphids and hypothesized that cover crop could provide a permanent habitat for pests.

Raper et al. (2004) mentioned problems with vibrations of the roller-crimper that get worse when the speed increases, a fact that could have stopped the adoption of the technology in the US. It could have negative health effects on the driver such as stomach pain, headache or spinal degradation (Kornecki et al., 2009). But it seems correlated with soil texture and humidity, and could be overcome with a proper design of roller-crimper (Raper et al., 2004).

Several studies were done with different vegetable crops after ASC termination. According to Feeser et al. (2014), the rolling technology is not suitable for all cash crop production. On this basis, a bibliographic review was done on the suitability of RC technology for different vegetable species (Appendix 2). It seems that the technique is adapted for most of the vegetable species mentioned, but due to few studies, it is generally difficult to conclude. The results strongly depend on climate, location and management.

***Economy.** The capital investment for new tools such as roller-crimper and strip-till may be high for small farmers. It could limit the adoption of the technique by many farmers (Morse, 1999; SoCo Project Team, 2009). Compared to bare soil, the farmers need also to buy a high amount of seeds for the cover crop.

The technique is complex and requires much technical knowledge to be successful (SoCo Project Team, 2009).

***Knowledge gap.** All researchers agree that there is a need for long-term results (Bàrberi, 2002; OSCAR project team, 2016; Reberg-Horton et al., 2012). As mentioned before, it seems that the effect on soil and weed community is different in short-term and long-term trials. Most of the research has been carried out on short-term experiments of 2-3 years or less due to financial constraints. Sometimes experimental plots are changed each year. More research needs to be done to provide technical support for farmers because the technique is not widely spread; references and material are missing for farm application (OSCAR project team, 2016; Peigné et al., 2007; Reberg-Horton et al., 2012).

More research also needs also to be done to study the effect on the environment since the technique is site specific, dependent on climate (OSCAR project team, 2016), soil type (Peigné et al., 2015), farmer management practices and field/farm history.

2.4. Hypothesis and research question

Given the context described above, the main question raised in this research is:

Is rolled winter ASC technology combined with strip tillage a good alternative to conventional tillage for organic outdoor organic vegetable production for weed control and soil fertility improvement?

To answer this question, the following five research sub-questions with their hypothesis, were raised:

(1) What are the agronomical performances of the different ASC mixtures and termination practices for squash production? Squash after RC[9] management should reach the same agronomical performances than GM[10] or bare soil[11] management (squash yield and quality), those performances would depend on ASC mixtures composition, biomass production, soil coverage and full termination success.

(2) Does RC technology increase weed control compared to conventional tillage and cover crop management practices? According to the bibliography conducted for this study, RC technique deters weed growth compared to GM and bare soil. It should also change weed community.

[9] **RC**: cover crop terminated with a Roller-Crimper and strip till cash crop transplanting
[10] **GM**: cover crop terminated as Green Manure, using a flail mower and incorporated into soil with tillage
[11] **Bare soil**: no cover crop

(3) Does RC management with reduced soil tillage improve soil quality and fertility? It is assumed that reduced soil tillage decreases soil compaction and improves soil structure. RC mulch should increase soil moisture due to soil permanent coverage.

(4) Is RC technique more sustainable for environment? RC should consume less fuel compared to GM (thus reducing GHG emissions).

(5) Does the technique of rolled winter cover crop associated with strip till have a higher or equal economic profitability than conventional management systems? RC technique reduces time spent for weeding and tillage operation compared to GM. Thus, if the hypothesis that RC management could produce the same squash yield and quality than GM or bare soil management is verified, RC technique could have the same profitability or even a better profitability compared to bare soil and GM.

This study will focus on rolling technique combined with strip till, which allowed to transplant easily the cash crop by hand in the strip already tilled and to fertilize the crop directly into the strip. A field experiment (FtA project) situated on GRAB's experimental farm was carried to answer these research sub-questions.

3. Materials and Methods

3.1. Research on ASC management at GRAB

On the basis of the organic vegetable production issues mentioned previously, GRAB began 3 years ago (2014), trials within the European project ”SoilVeg” to test cover crops associated with different termination techniques in order to implement and test the roller-crimper technique combined with strip till.

Two types of field trials (Ft) were carried out: Ft A and Ft B, done respectively with autumn/winter ASC followed by a summer cash crop and spring/summer ASC followed by an autumn cash crop.

In Ft B trial, there was a low ASC biomass production in 2015, ineffective mulch cover with buckwheat and high ASC regrowth that lead to low performance of broccoli. Therefore, Ft B trial has been stopped in 2016 due to high weed pressure, low cover crop seed germination, heterogeneity and the farm’s wish to stop. Spring cover crop establishment seems more difficult to manage than autumn ASC since ASC species need to be adapted to warm condition, to compete weed quickly and to be effectively killed by the roller-crimper.

Ft A has started in autumn 2015 and will end in September 2017. This experiment examines different winter ASC mixtures and different cover crop termination techniques. The cash crop transplanted by hand after the cover crops is butternut squash (*Cucurbita moschata* cv. ‘Ariel’, Sakata). This Master Thesis was done during the last year of the project on Ft A trial, with the possibility to refer to the previous year’s results, allowing analysis of the data collected on these techniques over time (see Appendices 4 and 10). The FtA project in 2016/2017 is based on the results of 2015/2016, especially regarding the design of the experimental plots on GRAB’s experimental farm.

This Master Thesis continues the work to optimize the use of autumn/winter cover crops, including its termination, to increase soil fertility, weed control and other benefits for organic vegetable fields.

To answer the problematic and hypothesis, the field trial FtA was used.

3.2. Location and experimental design

The experiment is located at GRAB experimental station (latitude**:** 43.906433, longitude**:** 4.884533, altitude**:** 33 m), next to Avignon, South-eastern France in the Mediterranean region, in Vaucluse department (see map on Figure 3). In the region Provence Alpes Côte d’Azur, organic farming is well developed, representing 18.3% of total France utilised agricultural area (ORAB PACA, 2016) with many fruit and vegetable growers.

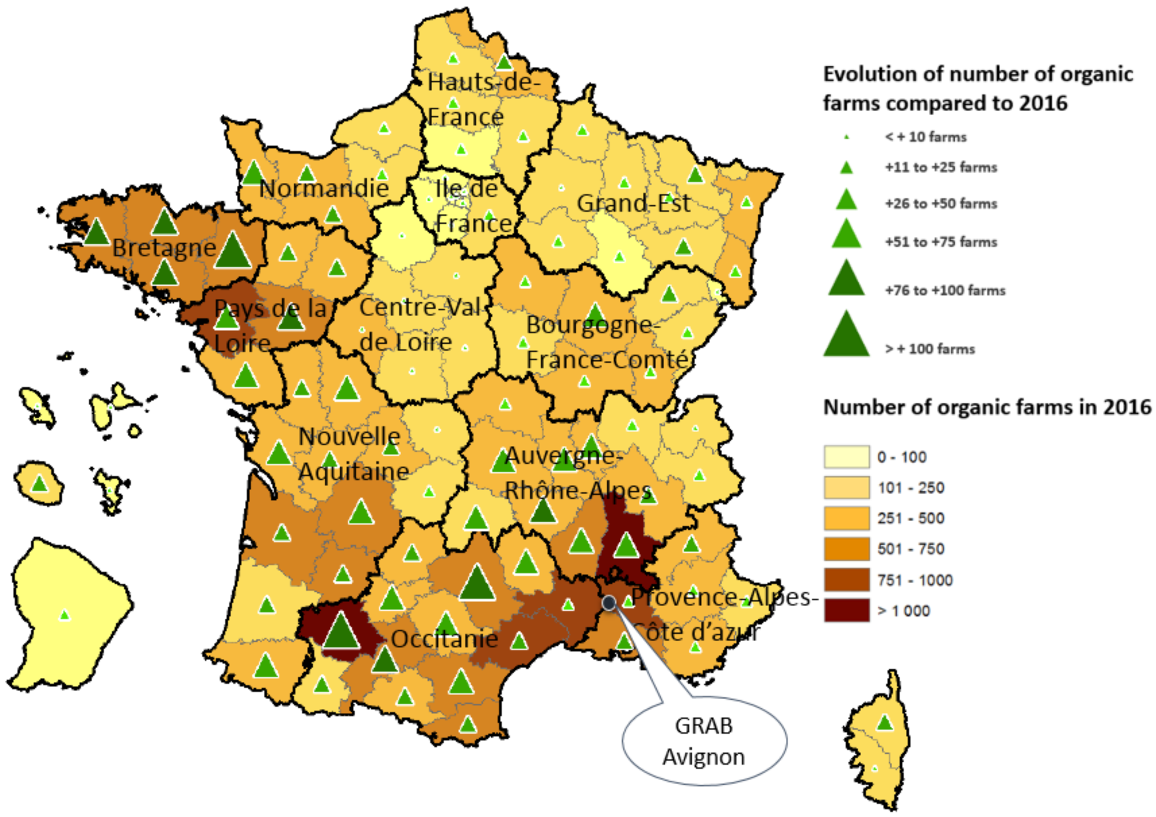


Figure 3: Number of organic farmers in France by region (Agence Bio, 2017)

According to the Köppen-Geiger climate classification, Avignon has a hot-summer Mediterranean climate (Kottek et al., 2006). Summers are warm with less rainfall than the rest of the year (Figure 4). The experimental plot was organically certified in 2002.

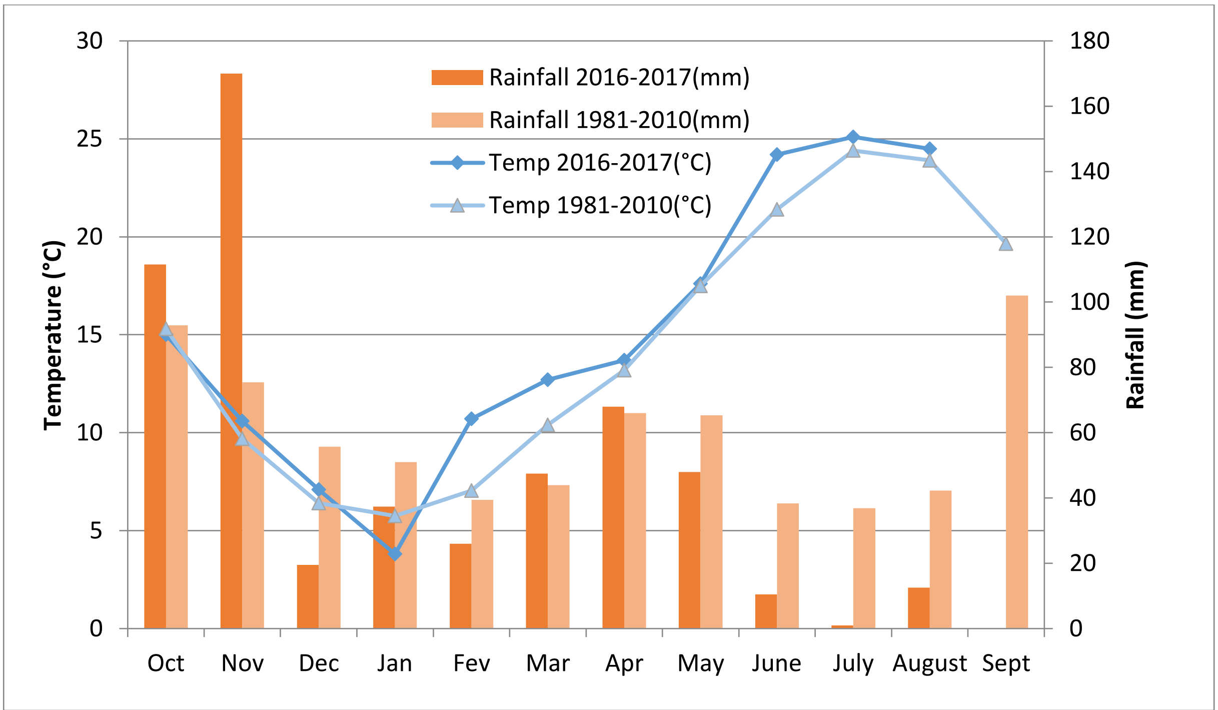


Figure 4: Avignon climate diagram (CIRAME Agrometéo)

The soil is a deep calcareous clay loam with a pH of 8.6 and 11,7% calcium carbonate. At the beginning of the experiment the soil organic matter level was 3.2% (C/N = 10,2) and bulk density around 1.6 mg m^{-3} (0-25 cm layer).

The experimental design is a complete block design with two blocks which were named north-south (N-S). In each block, two sub-blocks could have been taken as blocks, but were taken as repetition instead since they were not randomly assigned.

Two factors with three and two levels respectively:

- Factor 1 - ASC type:
    - ASC 1: rye [*Secale cereale*] + field pea [*Pisum sativum*]
    - ASC 2: winter barley [*Hordeum vulgare*] + fababean [*Vicia faba*] + field pea [*Pisum sativum*]
    - Control: “bare soil”, no cover crop. Weeds were mechanically killed with a flail mower when needed.

- Factor 2 - ASC termination strategy and soil tillage:
    - RC: roller-crimper combined with the strip till technique
    - GM: ASC shredding into green manure and incorporated into the soil

      In the Control plot, two soil tillage practices before the squash transplantation were also studied: strip tillage [Control ST] vs. conventional soil tillage [Control W] (tined cultivator followed by a rotary harrow).

On the borders of the experimental field, two other ASC were tested and treated as RC plots:

- ASC3: rye [*Secale cereale*] + fababean [*Vicia faba*] + hairy vetch [*Vicia villosa*]. This mixture was one of the level in the FtA 2015-2016 experiment, with problems of vetch regrowth after ASC termination.
- ASC4: winter barley [*Hordeum vulgare*]

The experimental design can be seen on Figure 5. ASC3 and ASC4 are placed at the borders of the plot with a limited number of measurements. The six combinations of factors were established in strips of 5 m wide and 50 m long (250 m²). Because of a possible “north-south” effect, we divided the plots into two main blocks. An area extending 10 m north of the experiment was not assessed because of the shade of a tall hedge, which creates differences in luminosity and soil humidity. The sampling plots had a surface of 100 m² (5 m x 20 m). Two lines of quash were transplanted with a 2.5 m wide inter-row and 40 cm distance between plants on the row (density of 1 plant per m²).

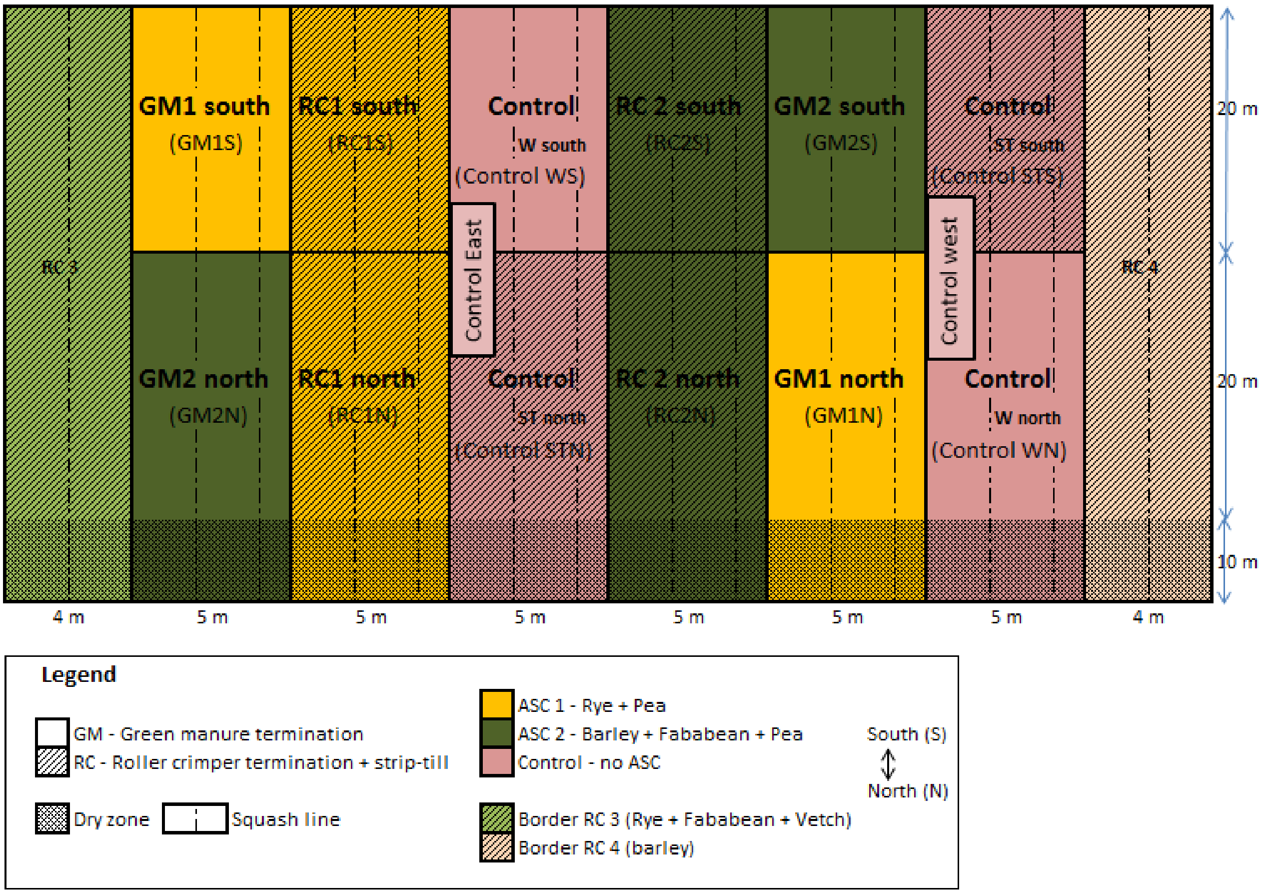


Figure 5: Experimental design FtA experiment (2016-2017)

The ASC levels were not situated exactly on the same place than in the last year experiment, to have more repetitions on GM1, GM2 and Control treatments (see experimental design of 2015-2016 in Appendix 3). Control and GM plots have respectively three and two times more repetitions than last year. One ASC (rye, fababean and vetch) experimented last year was taken out this year of the main experimental design. The plots were 6 m wide last year and only 5 m this year. A differentiation between north and south was made to better take into account the heterogeneity of soil humidity during the cash crop growth within plots because a problem was noticed in 2016.

3.3. ASC and crop management

The technical operations performed during the field experiment are summarized in the Figure 6. All the technical details on machinery used within the field are available in Appendices 5 and 6.

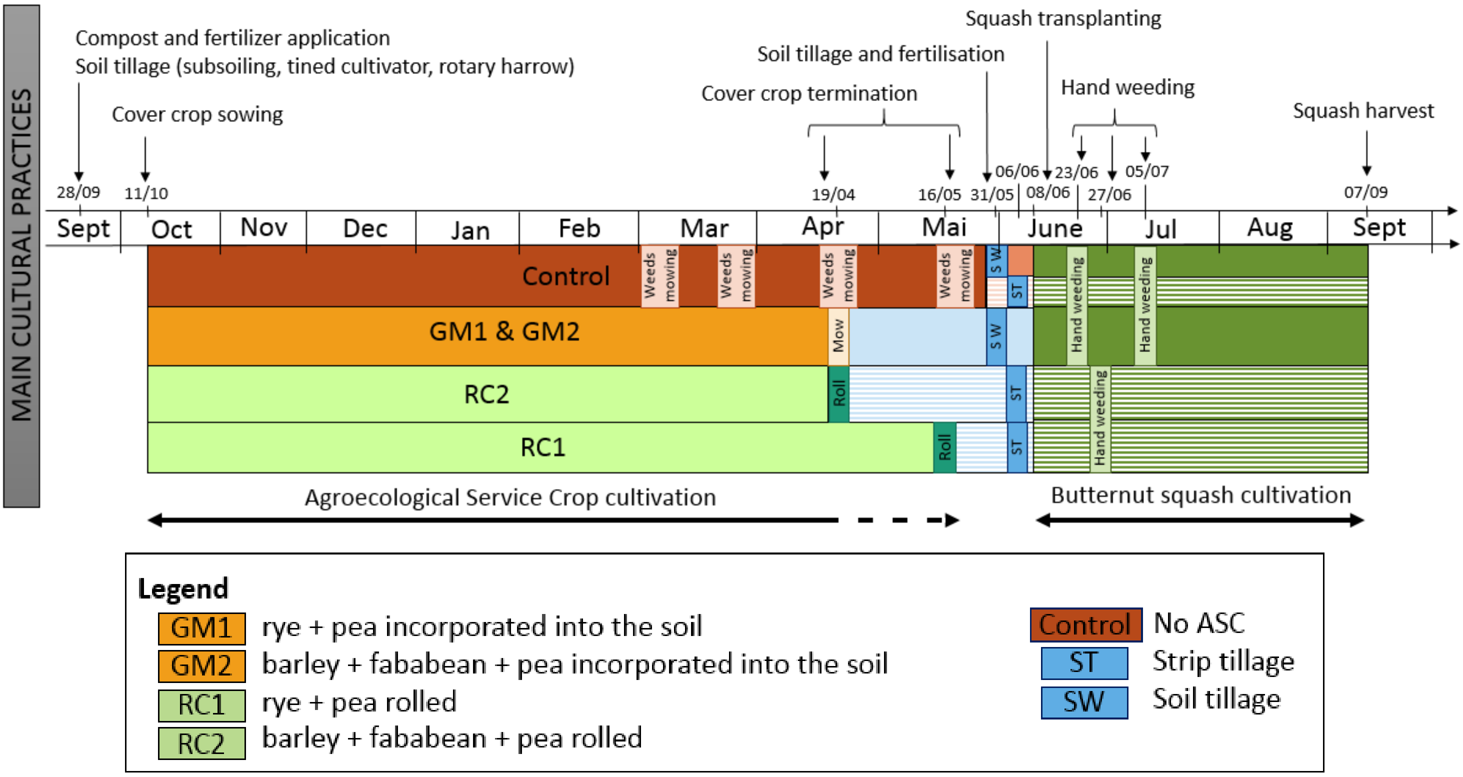


Figure 6: Crop management timescale diagram of FtA experiment (2016-2017)

Before seeding the ASC, on 28/09/2016, 2 Mg ha^{-1} of «Germiflor» fertilizer (6 – 7 – 10, chicken manure pellets) and 6 Mg ha^{-1} of compost (with approximately 65% plant residues and 35% horse manure) were applied on all plots.

Three tillage operations were done to prepare soil before ASC sowing on 29/09/2016: subsoiling (30 cm depth), tined cultivator (20 cm depth) and rotary harrow (20cm depth).

One complementary passage with a disc harrow was done on 11/10/2016 before ASC seeds were hand broadcast because a heavy rainfall of 36 mm occurred on 01/10/2016, creating soil slaking.

The sowing density of each ASC species in mixtures was high (Table 3). ASC1 and ASC2 were sown with 10% more than the pure dose, to maximise the weed competition and have the highest soil coverage. The leguminous species sowing density was increased in the mixtures in order to favour leguminous species since they are less competitive than grasses.

Table 3: Overview of agroecosystem service crop (ASC) mixtures, species and dosage for FtA

ASC	Species		Variety (Seed company)	Pure dose (kg ha^{-1})*	Dose (kg ha^{-1})	% of pure dosage
	Common name	Scientific name				
1	Rye	*Secale cereale*	Protector (Agrosemens)	120	60	50%
	Field Pea	*Pisum sativum*	Assas (Agrosemens)	160	96	60%
2	Barley	*Hordeum vulgare*	Baraka NT (Girerd)	150	50	33.3%
	Faba bean	*Vicia faba*	Irena (Agri Obtention)	200	80	40%
	Field Pea	*Pisum sativum*	Assas (Agrosemens)	160	60	37.5%
Control	No cover crop					
3	Rye	*Secale cereale*	Protector (Agrosemens)	120	40	33.3%
	Fababean	*Vicia faba*	Irena (Agri Obtention)	200	80	40%
	Hairy vetch	*Vicia villosa*	Minnie (AS)	50	20	40%
4	Barley	*Hordeum vulgare*	Baraka NT (Girerd)	150	150	100%

**from a technical review of Mohrmann (2016)*

To incorporate the seeds into the topsoil and favour germination, a light passage of a rotary harrow (2-3 cm) followed by a rolling was made the same day.

On control plots, weeds were flail mowed four times in spring (01/03/2017; 16/03/2017; 18/04/2017; 24/05/2017).

The ASC were terminated at different dates depending on their growing stage: ASC2 in April and ASC1 in May.

Picture 3: ASC1 mowing on 18/04/2017

All ASC on GM plots were killed with a hammer mower the 18/04/2017 (Picture 3). Then plant residues were superficially incorporated into the soil on 24/05/2017 with a rotary harrow (5cm depth).

Picture 4: ASC1 rolling

Picture 5: ASC2 rolling

RC2 was rolled on the 19/04/2017 a first time (Picture 5) and a second time one month later due to barley regrowth. RC1 was effectively rolled only one time on 16/05/2017 (Picture 4). RC2 was rolled one month before RC1 because barley was at late early dough stage (BBCH-scale 83) and needed to be terminated to avoid the production of viable seeds, which was the case last year. RC1 was terminated at medium milk stage (BBCH-scale 73).

Picture 6: Soil strip tillage combined with fertilisation (06/06/2017)

Organic fertilizer was applied on all the plots at a rate of 800 kg ha^{-1} of Dix (9-2-2)[12]. It was spread by hand on GM and control W plots the 31/05/2017 before soil tillage and directly on the strip till tine the 06/06/2017 for RC plots and control ST (Picture 6).

The soil was tilled on GM and Control W the 31/05/2017 with a passage of tined cultivator followed by a rotary harrow at 15 cm depth.

Picture 7: Squash transplantation and drip irrigation

Picture 8: Protecting nets

Drip irrigation was set up on the 07/06/2017 on all the squash transplantation lines (Picture 7).

Squash was hand transplanted the 08/06/2017 (Picture 7) and nets were used to protect the transplants against wind since the "Mistral" (Picture 8), a strong north-south wind in south of France, can cause damages. Ferramol (iron phosphate) was hand applied on squash rows the same day to minimize slug damages.

[12] Corresponding to: 72kg N – 16kg P2O5 – 16kg K2O

3.4. Measurements and data analyses

Parameters recorded are summarized on the timescale on Figure 7. Each parameter measured is linked with at least one of the five research question topics.

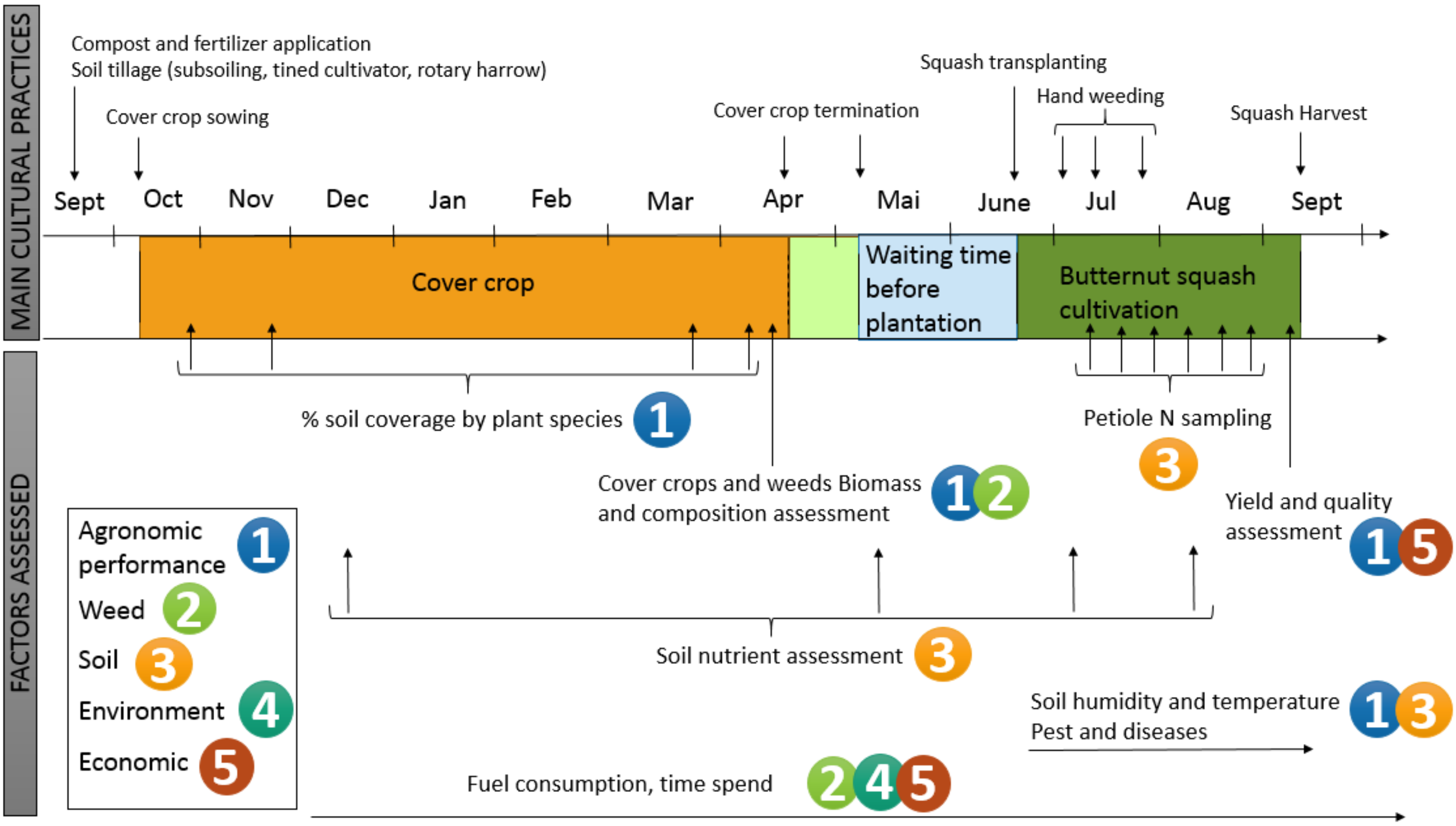


Figure 7: Timescale diagram with assessed parameters

A detailed methodology on parameter measurements is shown in Table 4.

Crop agronomical performance (1) was assessed during ASC and squash cultivation. ASC development was measured with the monitoring of specie's soil coverage during ASC's growth. Then, fresh and dried ASC biomass for each species was evaluated before its termination. ASC nitrogen and carbon content and C:N ratio were also measured. During the squash growing period, plant growth was recorded with notations on plant vigour and diseases and pests monitoring. Finally squash yields were measured.

Weed development (2) was evaluated during the ASC cycle as weed density and percentage of soil coverage. Weed fresh and dry biomass were weighed before ASC termination. Two weeks after squash transplantation, weed density was recorded on squash lines. Labour time for weeding operations during squash growth was also measured.

Soil (3) structure, nitrogen content and humidity were evaluated. During the squash cycle, plant nutrition was recorded with measurements on petiole's sap nitrogen.

During all the trial, fuel consumption (4) and time spent (5) for each cultural operation were measured. From these parameters, the economical profitability (5) was estimated.

Table 4: Parameter assessed, frequency and method used

Topic	Assessment	Sampling time	Methodology
1 – Agronomical performance	ASC germination	Two weeks after ASC sowing	Species density was measured with two repetitions on each experimental plot on quadrat of one m². Then percentage of germination was computed with the sowing density.
	% soil coverage	ASC cultivation, four times	During ASC cultivation, percentage of coverage for each ASC species was visually estimated.
	ASC Biomass	ASC termination	On each experimental plot with ASC (RC1, RC2, RC3, RC4, GM1 and GM2), ASC plants were harvested (cut with a knife at ground surface) on a quadrat of one m² with two replicates (making four replicates per treatments). Each species and weed plants were weighed, to obtain the fresh biomass produced per hectare for each species. A sample of each species per treatment was kept and weighed before and after 72h of proofer at 60°C. Then dry biomass was computed for each treatment. A representative sample for GM1N, GM1S, RC1N, RC1S, GM2N, G2S, RC2N, RC2S, rye, barley, field pea, fababean and vetch was sent to a laboratory for N and C content and C:N ratio measurements.
	Squash vigour	Squash cultivation (5 measurements)	A global score on a zero to five scale was given to assess visually plant vigour depending on plant colour, number of leaves, size of leaves and width and height of plants on the row. A note between 0 and 5 was given to assess squash's leaves colour (0: yellow; 5: dark green). Squash plant height was measured.
	Pest and disease occurrence	Squash cultivation	During the squash cultivation period, pests or disease contaminations were visually assessed, to explain possible squash yield reduction.
	Squash yield and quality assessment	Squash harvest	On sampling plots (described in Appendix 4), marketable and non-marketable squashes were classified. Then they were counted and weighed.
2 – Weed	Weed density	ASC cultivation	Seven weeks after ASC sowing, weed density was measured on three quadrats of 0.25m² each per experimental plot.
	% soil coverage	ASC cultivation, four times	During ASC cultivation, percentage of weed coverage was visually estimated.
	Weed Biomass	ASC termination	Fresh and dry biomass of weeds were measured on 2x1 m² per experimental plots

2 – Weed	Weed density	Squash cultivation	Two weeks after squash transplantation, weed density on squash lines was measured on three quadrats of 0.25m² each per experimental plot. Main weed species were distinguished (purslane, goosefoot and amaranth) and the other gathered into monocotyledonous and dicotyledonous group.
	Weeding labour time	Squash cultivation	All the manual weeding during squash cultivation was timed for all the treatments with distinction between east and west lines of squash.
3 - Soil	Soil nitrate and Water content	Four times: before ASC seeding, after ASC termination, mid and end squash cultivation	For each experimental plot, five samples were done at 0-30cm and 30-60 cm depth. Nitrate content was measured with the Nitracheck ® (Appendix 7) and water content was measured after 48h at 105°C.
	Soil bulk density Soil structure	Squash cultivation (2 times)	Soil Bulk density was measured by collecting 100 cm^3 of soil with a metal ring pressed into soil and determining the weight after drying. Measurements were done at 13 cm depth. Three repetitions were done on 27/07/2017 (RC1S, GM1S, Control WN and Control STS) and five on 07/08/2017 (RC1S and GM1S. Soil structure was visually assessed with a spade test and a “mini” soil profile (0.8m wide x 0.3 m deep). It was done on the same dates and treatments than bulk density measurements.
	Nitrate in squash petiole sap	Every two weeks during squash cycle (6 times)	One month after squash transplantation, nitrates in squash petioles sap were measured every two weeks. 12 petioles of young adult leaves were sampled on each experimental plot. The protocol of nitrate measurements can be seen in Appendix 8.
	Soil humidity and temperature	Squash cultivation	Soil moisture tension was assessed with tensiometers. It was measured on GM1S and RC1N at 15cm, 30cm and 45cm depth with two replicates. Soil Temperature was measured on GM2N, RC1N and Control STN at 10cm depth (every two hours recording with HOBO ® sensors). Rainfall was measured with a rain gauge and air temperature with a sensor.
4 -Environment	Fuel consumption	All the trial	For each cultural operation, the tractor was filled with diesel before and after going into the field to measure the quantity of diesel used. The surface worked was measured. Then, the fuel consumption for each cultural operation was computed. The distance between the diesel station and the field is 500 m.

5 - Economic	Labour time	All the trial	All the cultural practices (mechanical with a tractor or manual) were timed, on each experimental plot. Time for the tractor to come into the field was not included, neither the time for turning manoeuvres at the end of the rows. For roller-crimper and strip-till operations, the round trip was included (as it was done always in the same direction).
	Turnover and gross margin estimation	All the trial	Turnover was calculated with marketable squash yields harvested on the sampling plots and the organic retailer squash price. Gross margin was not computed due to lack of specific data. Instead, "gross margin differences" was calculated, not taking into account permanent costs which are the same for all the treatments (e.g. squash seeds, set nettings and irrigation, water, etc.). "Gross margin differences" was computed with the following formula: Gross margin differences = turnover - (ASC seeds price + Labour time price + Fuel consumption price) Following values were taken: Butternut squash price: 1.20 € kg^{-1} (wholesaler price in 2015-2016) Fuel price: 0.87€ L^{-1} Labour price: 13.86 € h^{-1} (SMIC + wage costs) Organic seeds costs: ASC1 -> 328.6 € ha^{-1} ASC2 -> 383.4 € ha^{-1}

Data analyses were done with Excel and R software (The R Foundation for Statistical Computing, 2017). Data processing, graphs and tables were done on Excel. Statistical analyses were carried out on the R software to compute analysis of variance (ANOVA) and non-parametric tests. All the errors bars in graphs and errors in the text represent the standard error.

4. Results

4.1. Agronomical performances

4.1.1. ASC development and biomass production

*** Germination**

Cereals had a lower germination rate compared to legumes (Figure 8). Rye had especially a low germination (between 15% and 35%) compared to barley (between 52% and 73%). The mean germination percentage for each species was 23% for rye, 60% for field pea, 61% for barley and 88% for fababean.

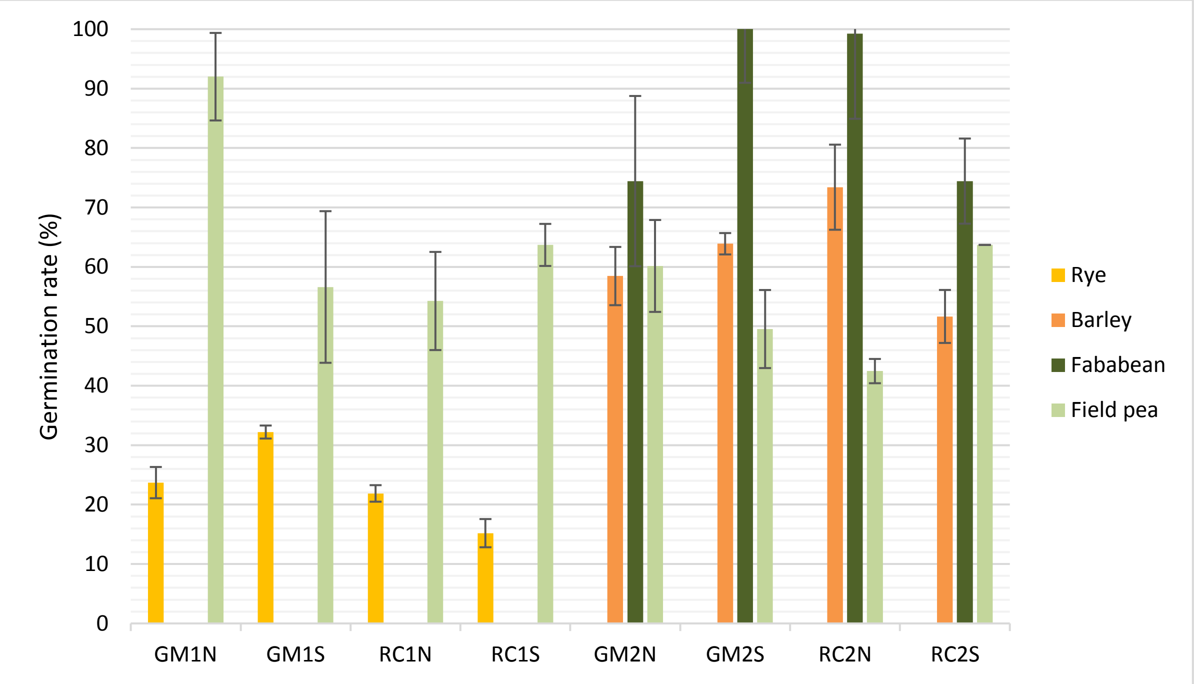


Figure 8: ASC germination rate per species for each treatment (see Figure 5, p 20) with error bars representing ± standard error.

*** ASC Development**

In both ASC1 (rye + pea) and ASC2 (barley + fababean + pea), weed soil coverage reached 18% and 20% the 14th March 2017 (Figures 9 and 10). It is only from the last week of March that cover crops competed strongly against weeds. This is correlated with a strong cover crop development then, due to higher temperatures, reducing weeds to 8% soil coverage (07/04/2017). This late competition effect could coincide with adverse weather conditions in autumn for cover crop development, including low temperatures and heavy rainfall (see weather recording in Figure 4, p 18).

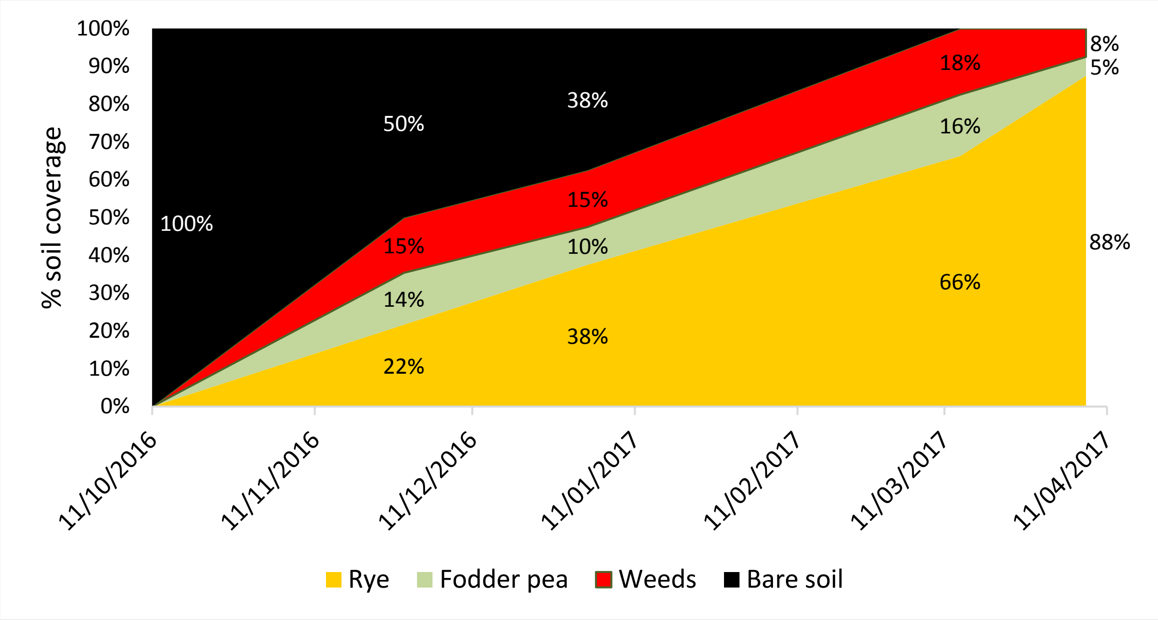


Figure 9: Percentage of soil coverage for the species of ASC1 and weeds

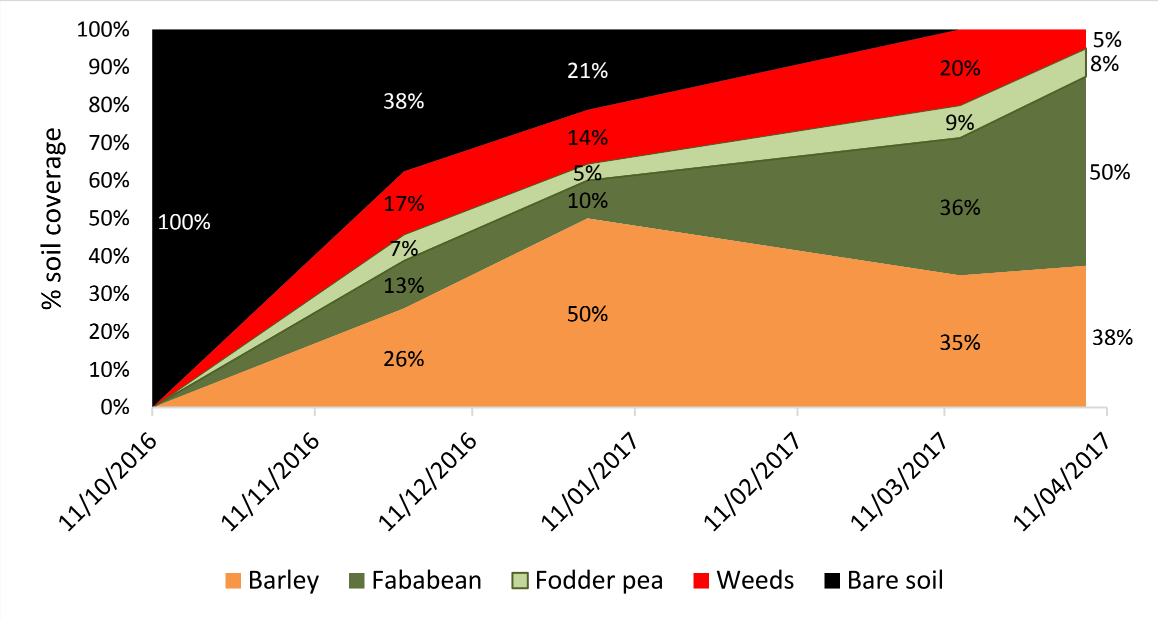


Figure 10: Percentage of soil coverage for the species of ASC2 and weeds

In ASC1, pea did not develop well compared to rye (5% vs. 88% soil coverage on 07/04/2017), even if it had a correct germination rate and growth the first month. The same observation was done in ASC2; thus pea was not competitive in the mixtures. In ASC2, fababean started to grow after January to finally cover more soil than barley, competing barley growth due to high light competition.

*** Biomass production**

Dry biomass of ASC1 (10.3 Mg ha^{-1}) was statistically larger than ASC2 (8.7 Mg ha^{-1}) (Figure 11). More cereal biomass was produced in ASC1 compared to ASC2 because rye produced twice the barley biomass.

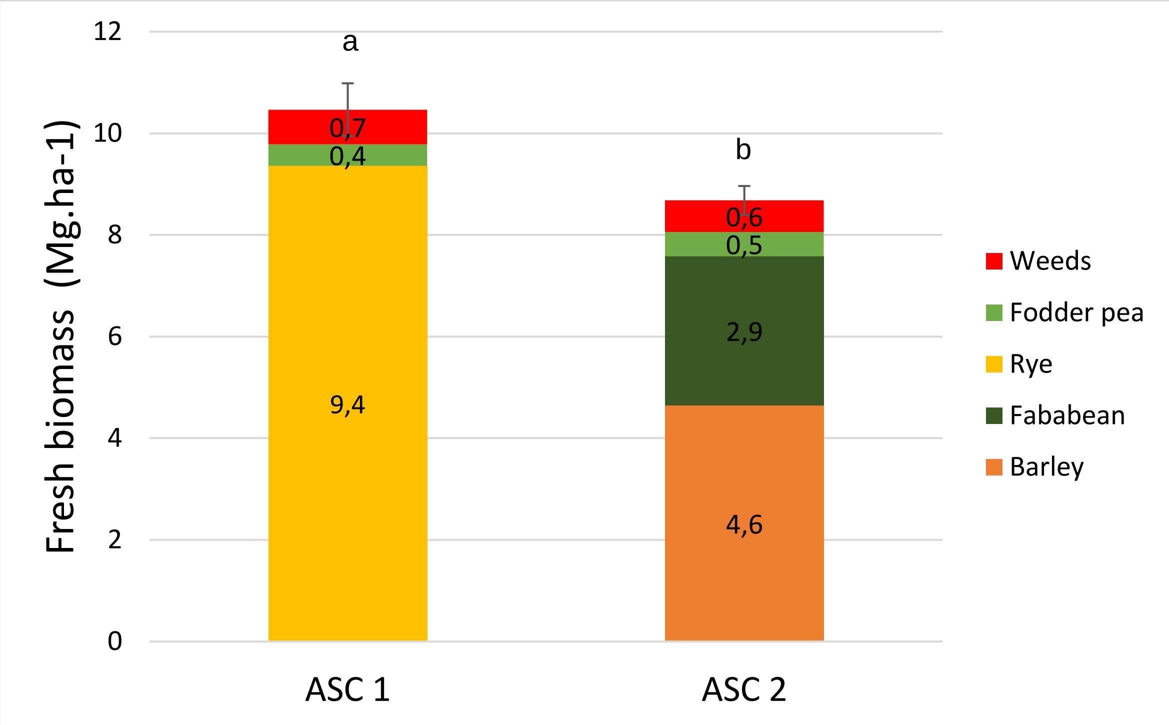


Figure 11: ASC dry biomass measured on 13/04/2017. Error bars represent ± standard error and letters above bars indicate significant differences at P < 0.05 level using Fisher's LSD test.

Total ASC nitrogen biomass was higher in ASC2 than ASC1 (Table 5).

Table 5: ASC nitrogen content on experimental plots

	C/N ratio ± s.e.	**Total N (kg ha^{-1}) ± s.e.**
ASC1	24.3 ± 1.3	194 ± 16
ASC2	16.0 ± 0.6	238 ± 11

4.1.2. Squash development

*** Squash plant Vigour**

Squash on tilled plots (GM1, GM2 and Control W) were more vigorous than squash on strip-tilled plots (RC1, RC2 and Control ST) (Figure 12). Throughout squash development, GM1 and GM2 had similar vigour. Squash leaves on RC were yellowish and smaller than other treatments. The three vigour indicators used show similar classification of squash vigour between treatments.

Vigour differences were already observed one month after transplanting (07/07/2017), squash on GM plots being "greener" with larger and higher plants than the other treatments.

On 17/07/2017, vigour differences between RC and Control plots were observed. In ascending order, vigour treatment ranking was RC1 < RC2 < Control ST (Control with strip tillage) < Control W (Control with soil tillage). These differences were noticed during all subsequent measurements. At the end of July, squash on Control W plot had similar vigour than GM plots.

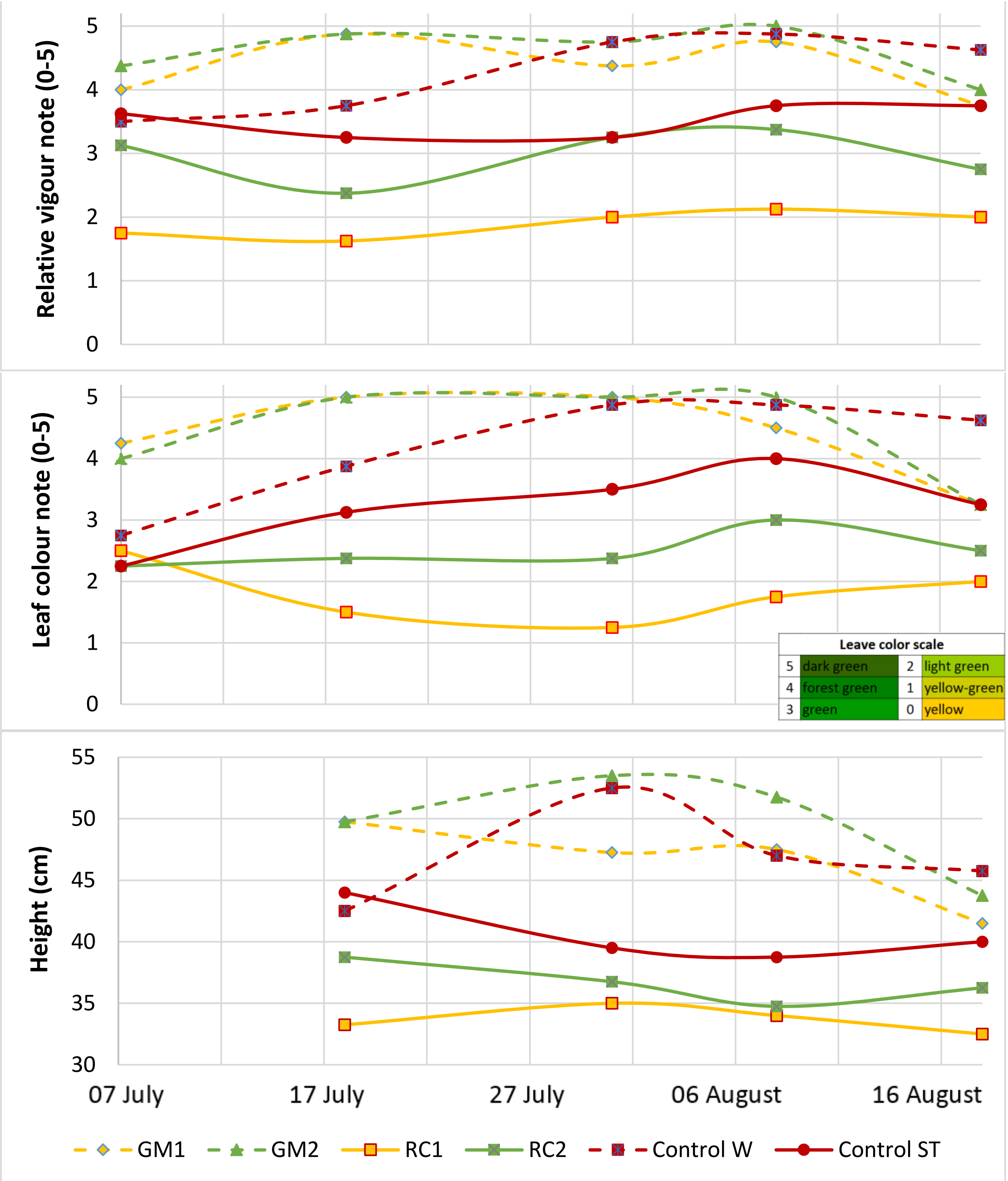


Figure 12: Squash vigour, leaf colour and plants height throughout the squash growing period for each treatment (see Figure 5, p 20)

4.1.3. Squash yield

The tilled plot a had higher yield compared to strip-tilled treatments had a lower yield (Figure 13). Soil tillage strongly increased squash yield (p-value=1.59e-12). It explains most of the differences between treatments. ASC factor had a small statistical effect (p-value=0.028). RC1 yield was statistically lower than RC2. Nevertheless, no statistical yield difference between GM1 and GM2 was measured.

Non-marketable squash percentages were low, between 1.5 and 3.5% (Figure 14) and no statistical differences were observed. Fruits weighted in average 0.170 kg more on GM treatments than the other treatments (Figure 15).

A statistical difference in fruit number production per hectare was observed. More fruits were harvested on Control W, GM2 and GM1. Then, 20 625 squash fruits per ha were produced on Control ST. Less fruits were measured on RC2 and RC1 (Figure 16). These differences were identical to the one observed for total squash yield.

Squash yield differences were the result of a higher number of fruits per m² on tilled soil treatments (GM and Control W) and higher fruit mean weight on GM treatments.

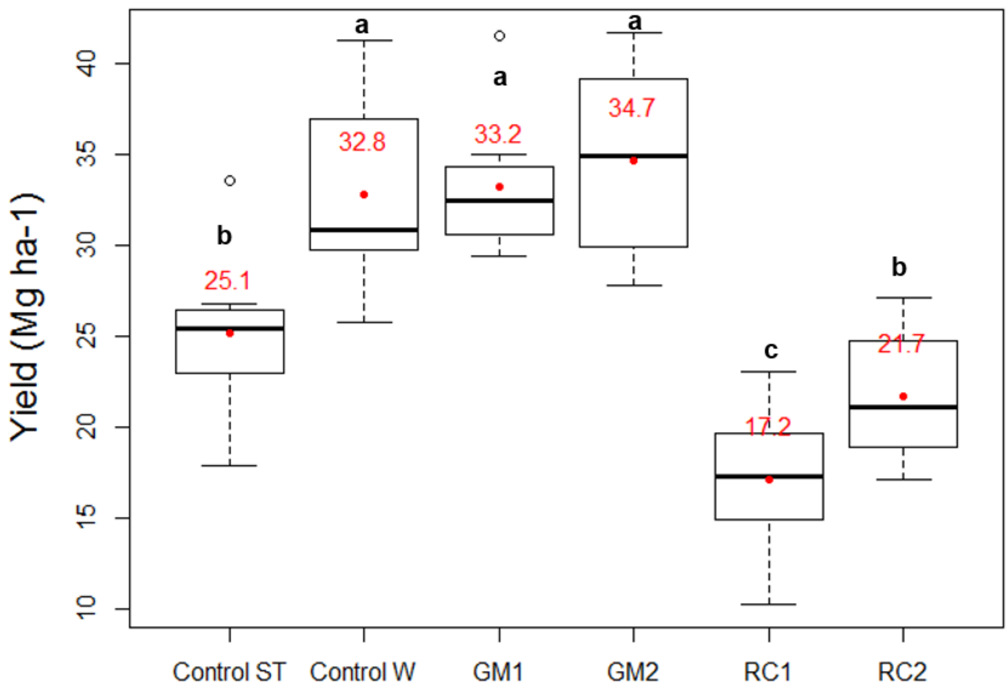


Figure 13: Total squash yield per treatment (marketable and non-marketable fruits). Letters above box indicate significant differences at P < 0.05 level using Fisher's LSD test. The line within the box represents the median; the box represents 50% of the data; whiskers represent the 10th and 90th percentiles; the red points represent the mean; n = 8.

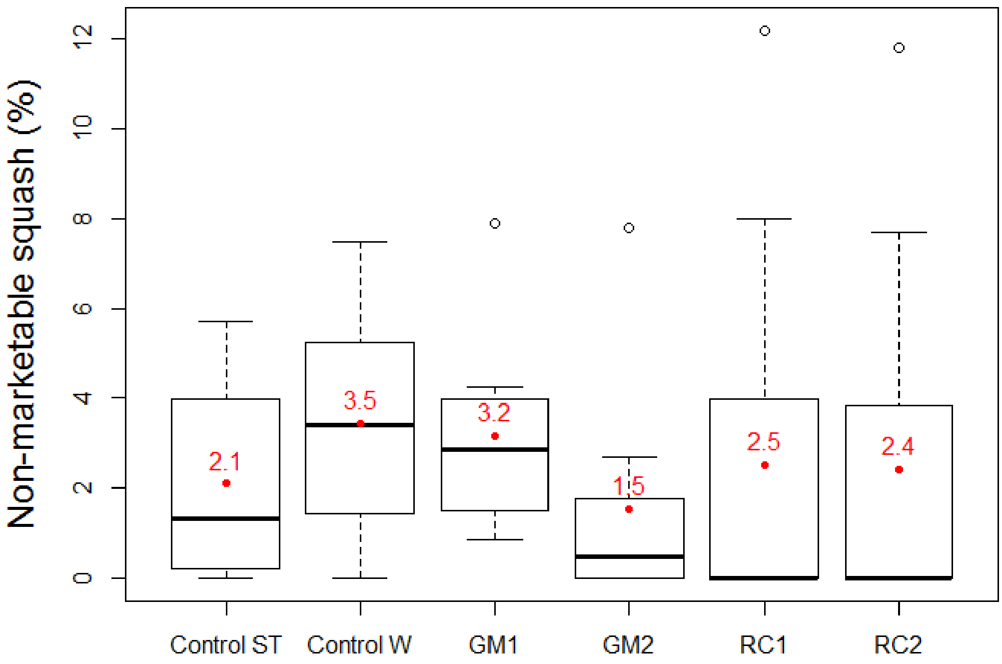


Figure 14: Percentage of non-marketable squash per treatment (non-marketable fruits = green, weight inferior to 500g or damaged fruits). No statistical differences at $P < 0.05$ level using Kruskal-Wallis test. The line within the box represents the median; the box represents 50% of the data; whiskers represent the 10th and 90th percentiles; the red points represent the mean; n = 8.

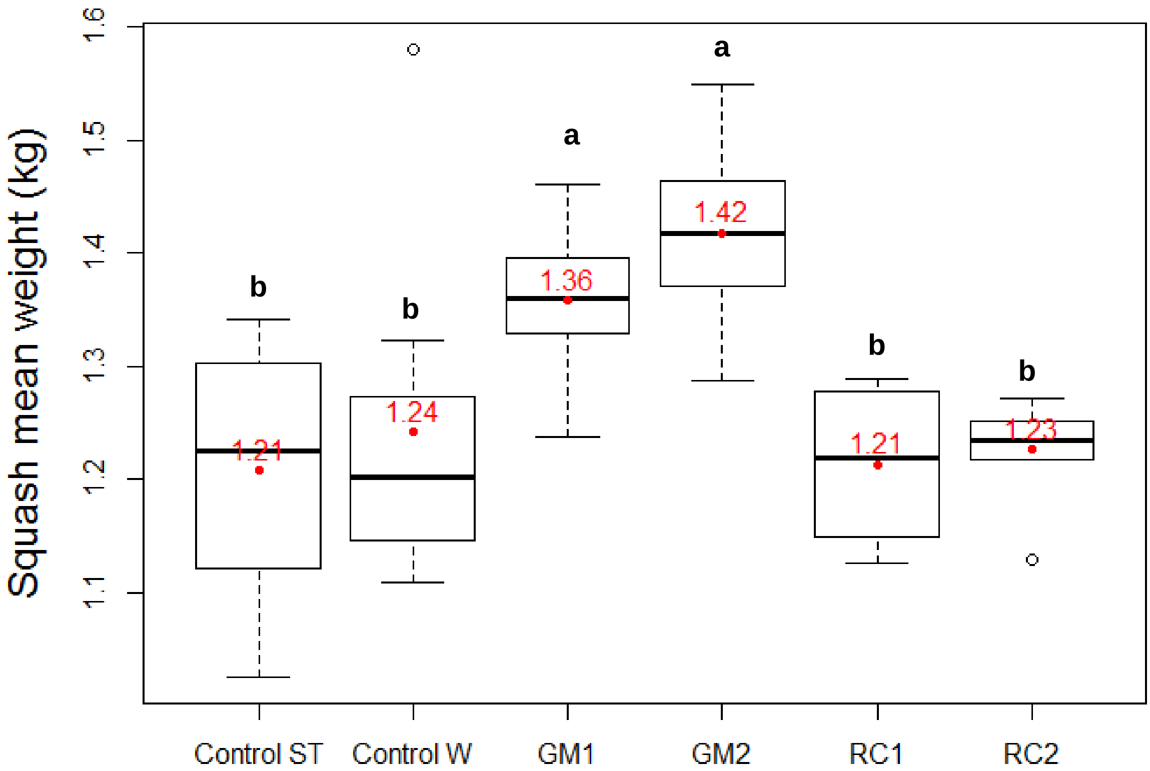


Figure 15: Marketable fruit mean weight per treatment. Letters above box indicate significant differences at $P < 0.05$ level using Dunn's test. The line within the box represents the median; the box represents 50% of the data; whiskers represent the 10th and 90th percentiles; the red points represent the mean; n = 8.

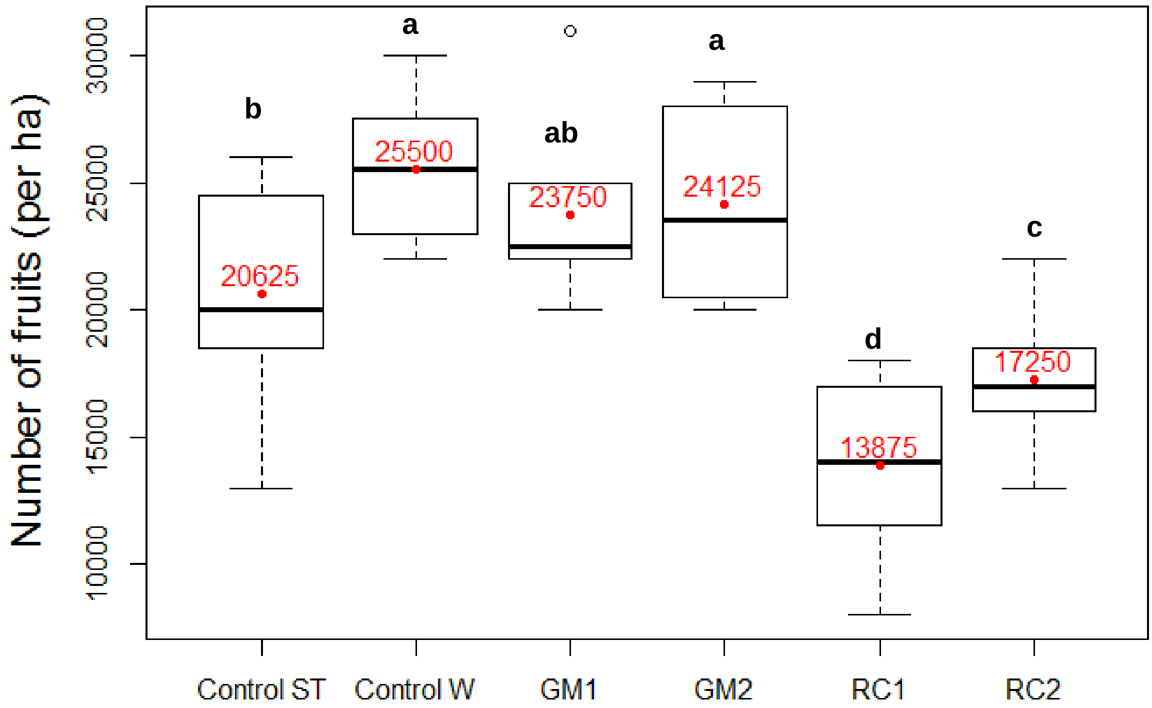


Figure 16: Number of marketable fruits per treatment per ha. Letters above box indicate significant differences at P < 0.05 level using Fisher's LSD test. The line within the box represents the median; the box represents 50% of the data; whiskers represent the 10^{th} and 90^{th} percentiles; the red points represent the mean; n = 8.

4.2. Weed development

4.2.1. During ASC cycle

Control West and GM1S&GM2N had the highest weed density (Table 6). RC1 had 63 weed per m^2. Control East had the lowest weed density even if no ASC was sown. It is explained by low ASC development (15-20 cm height) that did not impact weed emergence. This is correlated with weed coverage measurements done later during ASC growth. It was particularly visible for the differences in weed coverage and composition between the east Control plot and the west one. Control West plot had at least 50% more weeds than the East one. These results are correlated with the RC and GM levels location in the experimental design last year (see part 5.2.2.).

Table 6: Weed density and percentage of weed coverage during ASC development per strip (see Figure 17). For weed density on 28/11/2017, the values in column followed by a different letter are significantly different according to Fisher's LSD test at P < 0.05.

	Weed density (per m²)		Weed coverage			
	28/11/2017		28/11/2017	02/01/2017	14/03/2017	07/04/2017
RC1	63 ± 11	b	16%	15%	23%	10%
RC2	36 ± 6	bc	9%	10%	15%	5%
GM1S&GM2N	103 ± 17	a	26%	24%	20%	5%
GM1N&GM2S	46 ± 11	bc	12%	10%	18%	5%
Control West	133 ± 13	a	33%	70%	100%	60%
Control East	24 ± 7	c	6%	10%	50%	30%

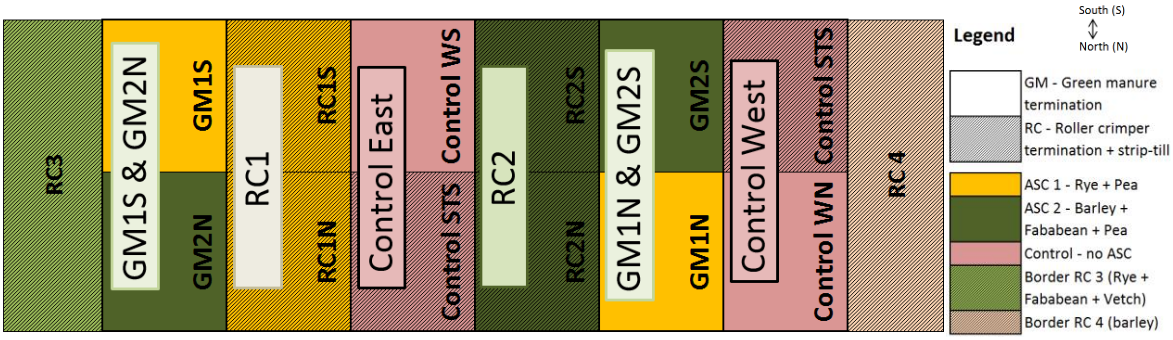


Figure 17: Simplified experimental design with treatments and strips names

No statistical difference on weed biomass harvested on the 13/04/2017 was observed between ASC type (Figure 18). The mean weed dry biomass harvested ranged from 0.24 (s.e. 0.12) for RC1S to 1.09 Mg ha^{-1} (s.e. 0.45) for RC2N.

Weeds identified in March were *Capsella bursa pastoris*, *Lamium amplexicaule*, *Leontodon proteiformis*, *Poa pratensis*, *Senecio vulgaris*, *Stelaria media* and *Veronica persica*. *Senecio vulgaris* represented a high percentage of weeds, especially on the borders of the plots. At the end of ASC cultivation, *Sonchus* spp. (*asper*, *arvensis* and *oleraceus*) developed and represented a high weight in the weed biomass measured.

More Gramineae such as *Poa pratensis* were observed on Control West, which looked like a lawn, whereas Control East which had a higher number of dicotyledonous species.

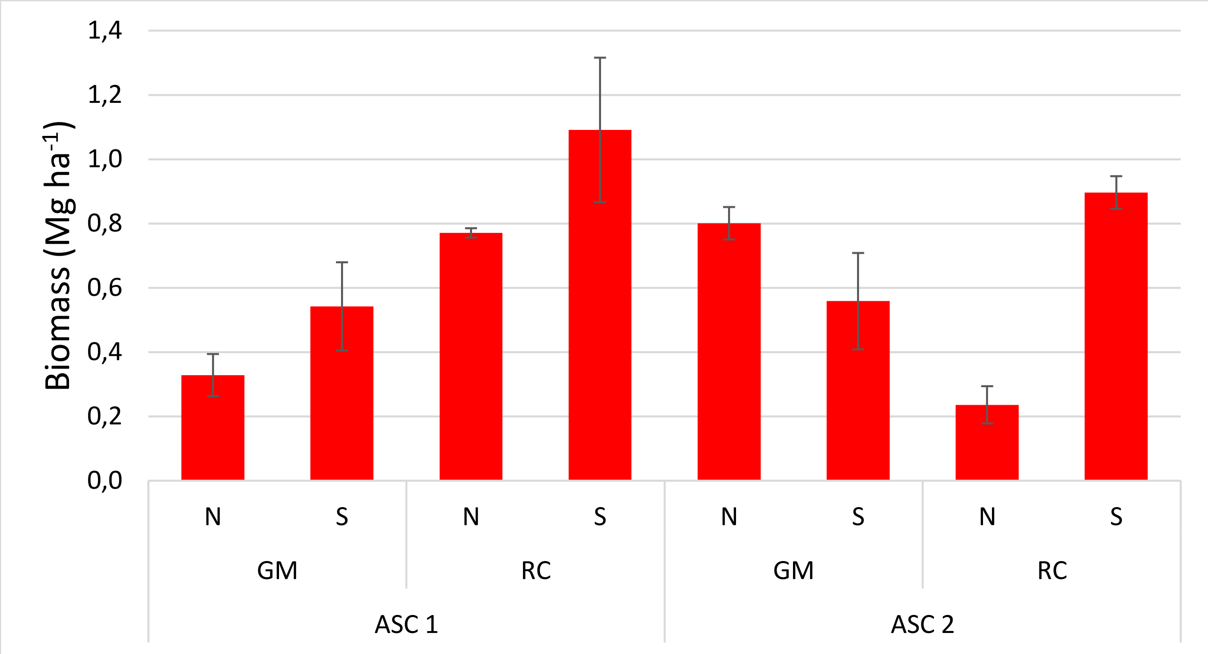


Figure 18: Weed dry biomass for each plot on 13/04/2017 (*error bars: standard errors*)

Before squash transplantation, some *Chenopodium* spp., *Convolvulus arvensis, Conyza* spp., *Helminthotheca echioides, Picris hieracioides, Podospermum laciniatum* and *Symphyotrichum subulatum* were noticed on no-tilled plots where the ASC had been terminated since three (RC1) to seven (RC2) weeks. These weed species were maybe already present before ASC termination.

4.2.2. During squash crop cycle

Strip-tillage operation reduced highly the number of weeds compared to soil tillage (Figure 19). RC1, RC2 and Control ST had at least four times less seedlings than GM2 or Control W treatments. GM1 (224 weeds per m^2) had two times less weeds than GM2 (543 weeds per m^2) and Control W (568 weeds per m^2). When mowed and incorporated into the soil, ASC1 had reduced weed emergence compared to ASC2.

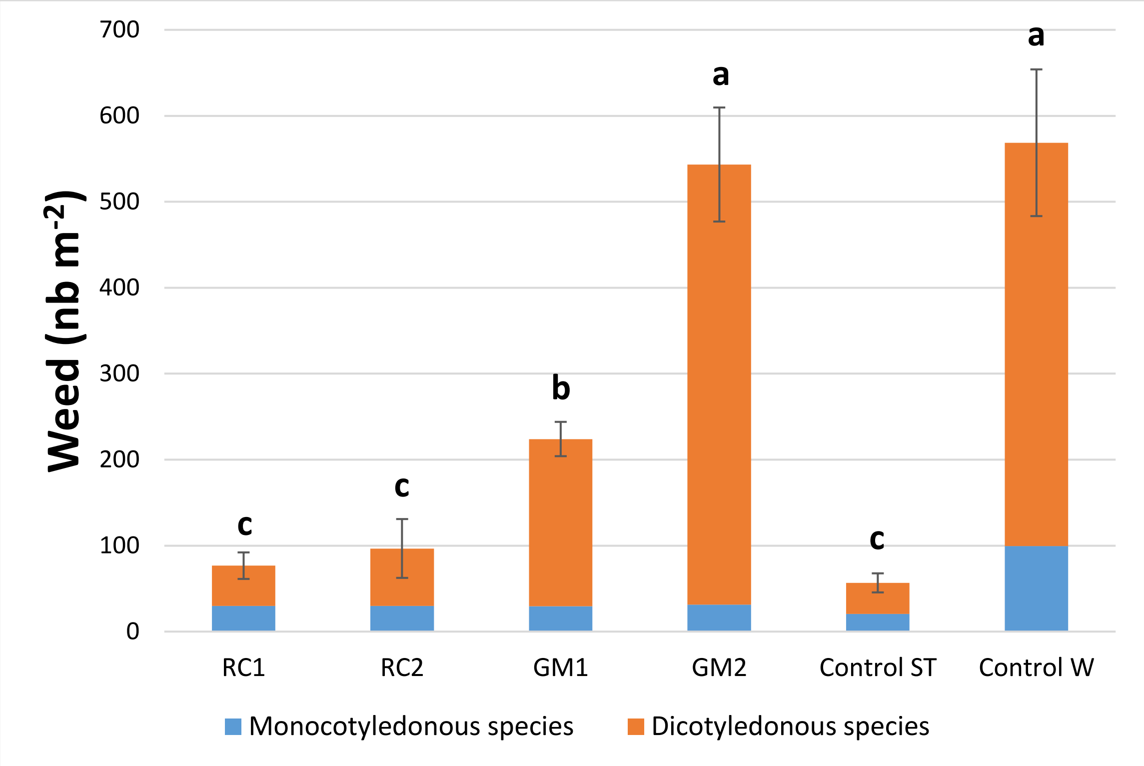


Figure 19: Weed density on squash rows two weeks after squash transplantation (22/06/2017). Error bars represent ± standard error and letters above bars indicate significant differences at P < 0.05 level using Fisher's LSD test with a square root data transformation and p.adjust=BH.

Most of the weeds were dicotyledonous species (Table 7). Monocotyledonous species number was around 30 per m^2 for all treatments, except for Control W (99.3 per m^2). Major dicotyledonous species were purslane (*Portulaca oleracea*) and amaranth (*Amaranthus* spp.). Purslane was clearly favoured by soil tillage (GM and Control W), where it represented 59 to 73%, compared to only 1 to 22% in strip-tilled plots (RC and Control ST). Amaranth was observed on all plots, representing between 8 to 27% of total weeds. Other dicotyledonous species identified were *Conyza* spp., *Chenopodium* spp., *Helminthotheca echioides, Convolvulus arvensis* and *Picris hieracioides*. Monocotyledonous species identified were *Echinochloa crus-galli* and *Setaria viridis*.

Table 7: Weed species percentage for each treatment

	RC1	RC2	GM1	GM2	Control ST	Control W
Portulaca oleracea	1%	11%	59%	73%	22%	60%
***Amaranthus* spp.**	27%	11%	18%	8%	20%	16%
Other dicotyledonous spp.	33%	47%	10%	13%	21%	7%
Monocotyledonous spp.	39%	31%	13%	6%	36%	17%

Weeding workload was lower in strip-tilled plots, between 72 h ha^{-1} for RC1 and 131 h ha^{-1} for Control ST (Figure 20). GM2 had the highest weeding workload with 362 h ha^{-1}. Strip tilled plots required statistically less weeding than tilled plots. GM1 required statistically less weeding than GM2 with 280 h ha^{-1} whereas Control W needed 324 h ha^{-1}. RC plots required only one weeding passage on 13/06/2017 compared to other treatments. Manual weeding time correlated with weed emergence measured two weeks after squash transplantation (Figure 19).

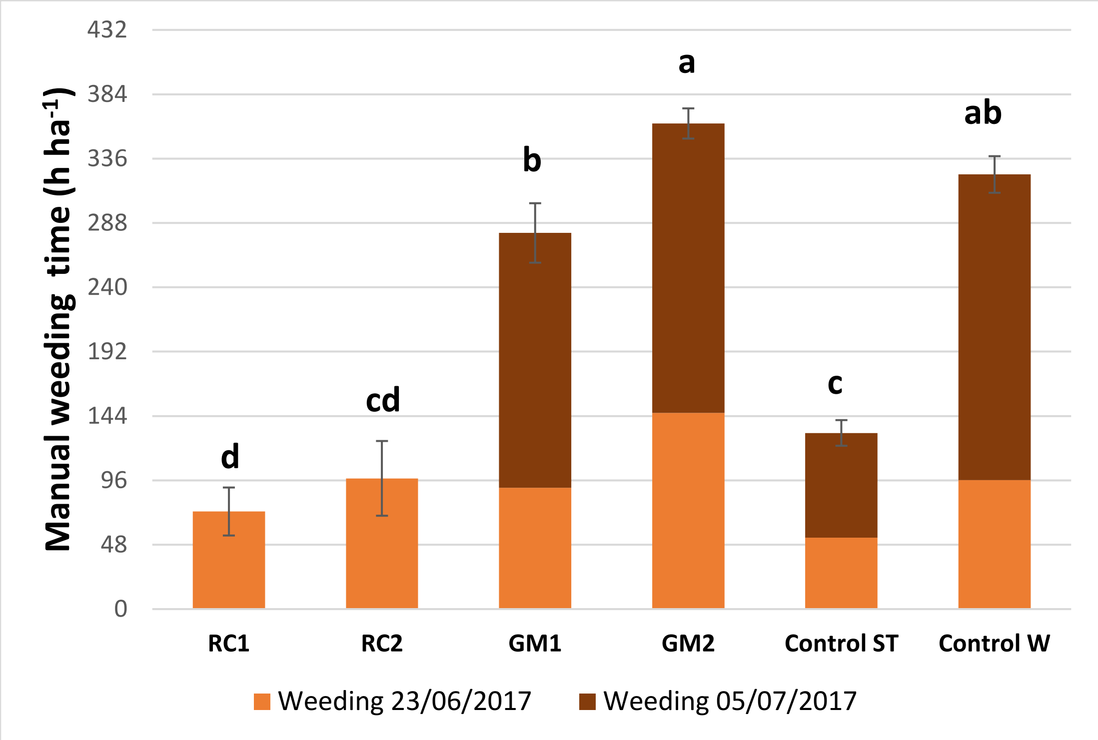


Figure 20: Manual weeding time during squash cultivation. Error bars represent ± standard error and letters above bars indicate significant differences at P < 0.05 level using Fisher's LSD test with p.adjust=BH.

4.3. Soil quality and fertility

4.3.1. Soil nitrate content

During ASC cultivation, nitrate content decreases for all treatments, also on Control plots even if no ASC was cultivated (Figures 21 and 22). It could be explained by nitrate leaching one month after ASC sowing due to high rainfall and poor development of ASC. Thus, around 50 kg ha^{-1} of NO_3^- could have been leached. Nevertheless, soil nitrate content on Control plots was two times higher on 30-60 cm layer on 18/05/2017 compared to other treatments. This decrease of NO_3^- was more observed on the deep soil layer (30-60 cm) than on top soil surface (0-30 cm). On 20/07/2017, nitrate soil content increased after soil fertilisation (72 N units per ha), especially on the 0-30 cm soil layer.

Soil nitrate content was not a satisfactory measurement to compare soil fertility between treatments. It did not reflect differences of squash vigour (see Figure 12), certainly more directly linked to squash N nutrition. Thus, squash petiole's sap nitrate was used to directly access squash N nutrition.

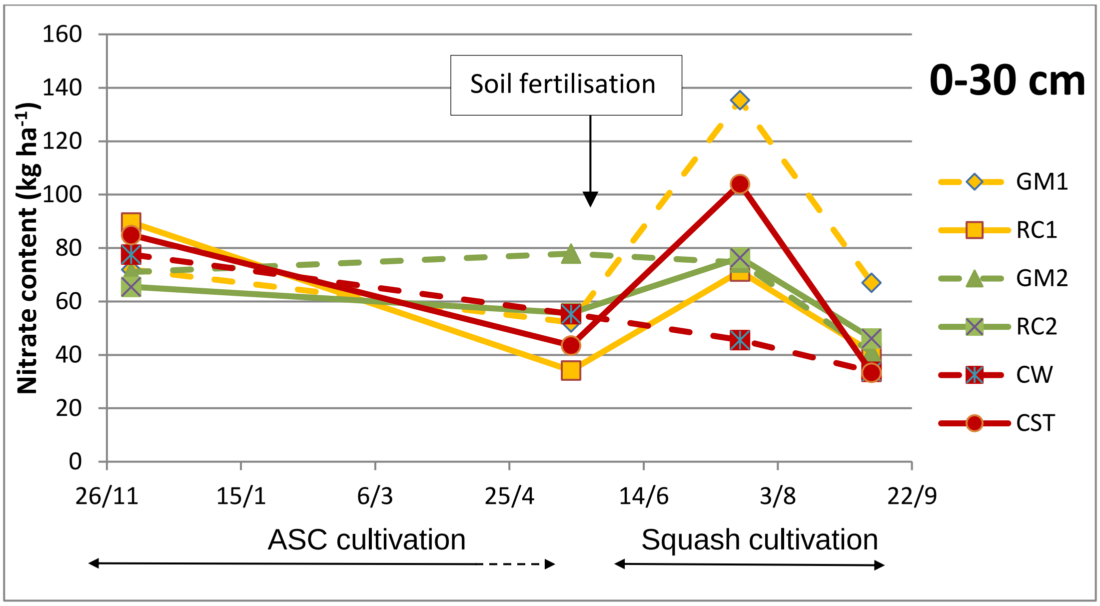


Figure 21: Soil nitrate content in the 0-30 cm soil layer

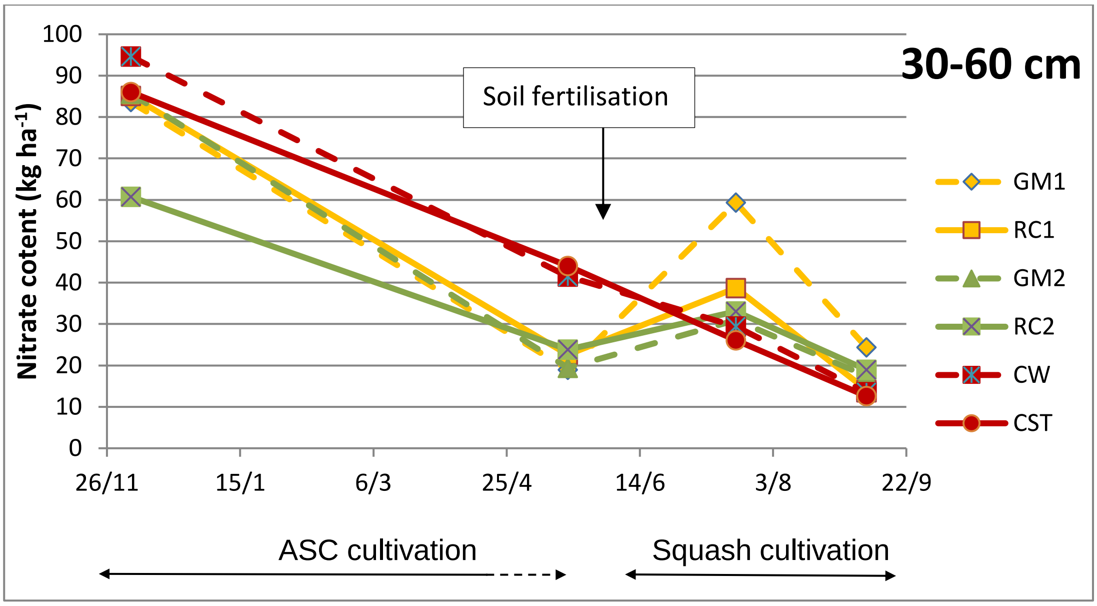


Figure 22: Soil nitrate content in the 30-60 cm soil layer

4.3.2. Squash petioles' sap nitrogen content

Two weeks after squash transplanting, nitrate in squash petiole's sap was at least six times higher in GM treatments (3142 mg L^{-1}) than strip-tilled plots (RC1: 515 mg L^{-1}; RC2: 150 mg L^{-1}; Control ST: 275 mg L^{-1}) (Figure 23). The high nitrate content in GM treatments exponentially declined then. Squash on Control W treatment had a higher nitrate rate compared to control ST. Thus, squash on tilled plots had a higher nitrogen content in petiole' sap than on strip tilled plots. RC treatments had a slightly lower nitrogen nutrition status than Contol ST.

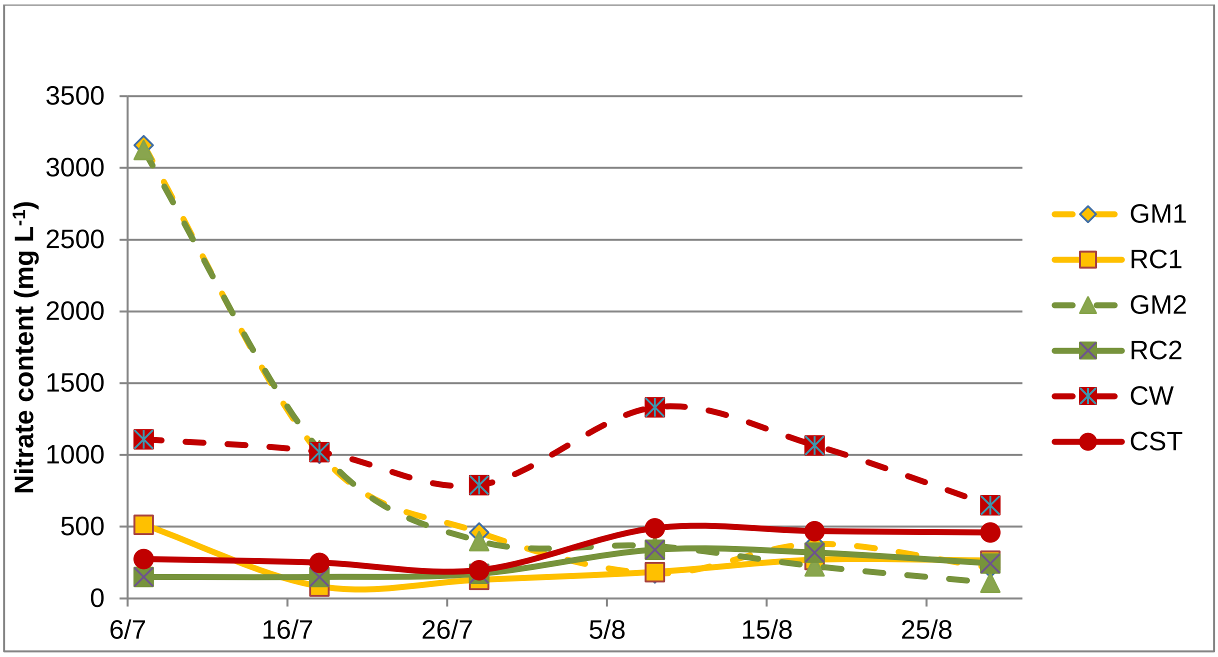


Figure 23: Nitrate levels in squash petioles' sap during squash cultivation

Even if the fertilizer amount (70 N unit per ha) was localized on squash transplanting rows on RC treatments (it was not localized last year and then not available for plant due to dry weather conditions), it was not sufficient to produce the same squash yield compared to tilled soil. Thus, fertilisation was not the only explaining factor of vigour differences. Nevertheless, squash yields were higher this year on RC compared to last year (+ 5 to 6 Mg ha^{-1}).

4.3.3. Bulk density

Visual assessment through a spade test and "mini" (0.8m wide x 0.3 m deep) soil profile on 27/07/2017 showed that soil was more compacted on RC1S and Control ST than on Control WN and GM1S. When soil profile was done on RC1S (07/09/2017), the soil was very humid and compacted (Picture 9). It has a bright reflection which is synonyms of anaerobic conditions. Soil porosity was higher in GM than RC treatments. Squash roots were shallow and close to soil surface on RC1S compared to squash on GM1S which had a more developed rooting systems going deeper into soil (Picture 10).

Picture 9: Mini soil-profile on RC1S (07/09/2017)

Picture 10: Mini soil profile on GM1S (07/09/2017)

Bulk density at 13 cm depth was lower on GM1S (1.24 g cm^{-3}) than on Control plots (Figure 24). Within control treatments, the tilled one had a lower bulk density (1.41 g cm^{-3}) than the no-tilled (1.54 g cm^{-3}). Soil density on RC1S (1.31 g cm^{-3}) seemed to be not correct since the soil structure was visually more compacted than Control WN. Thus, a second soil visual assessment and apparent density measurement were done at the end of the crop, the 07/09/2017 (Figure 25). Bulk density was significantly much higher in RC1S (1.50 g cm^{-3}) than GM1S (1.19 g cm^{-3}) which was in accordance with visual assessment.

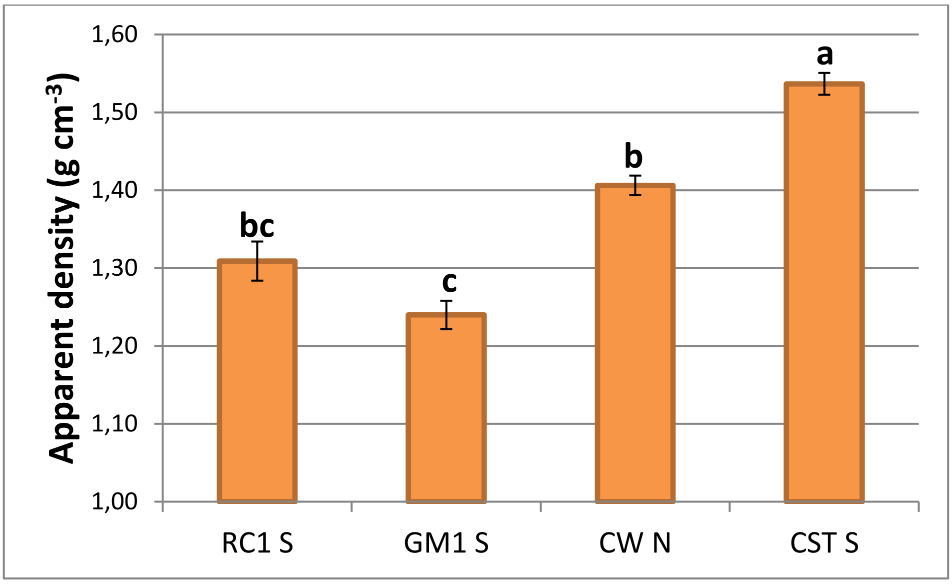


Figure 24: Bulk density (27/07/2017). Error bars represent ± standard error and letters above bars indicate significant differences at P < 0.05 level using Fisher's LSD test.

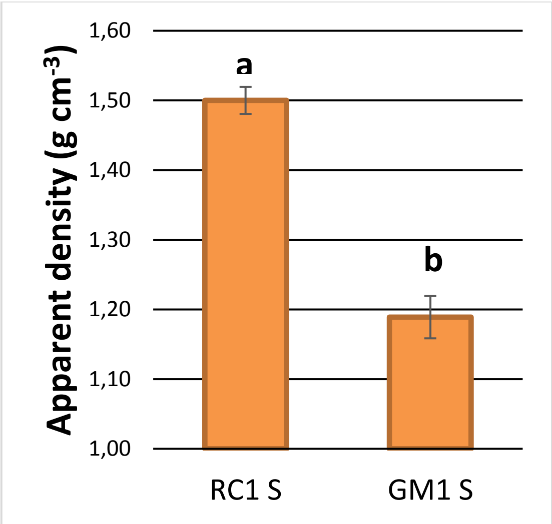


Figure 25: Bulk density (07/09/2017). Error bars represent ± standard error and letters above bars indicate significant differences at P < 0.05 level using Fisher's LSD test.

4.3.4. Soil temperature and humidity

Soil temperature was higher in GM2N than Control STN, especially the first week after the beginning of the measurements (Figure 26). Soil temperature in RC1N was lower in the afternoon during most of the squash cultivation period. The combined effect of reduced soil tillage and ASC1 mulch has reduced the soil temperature on RC1.

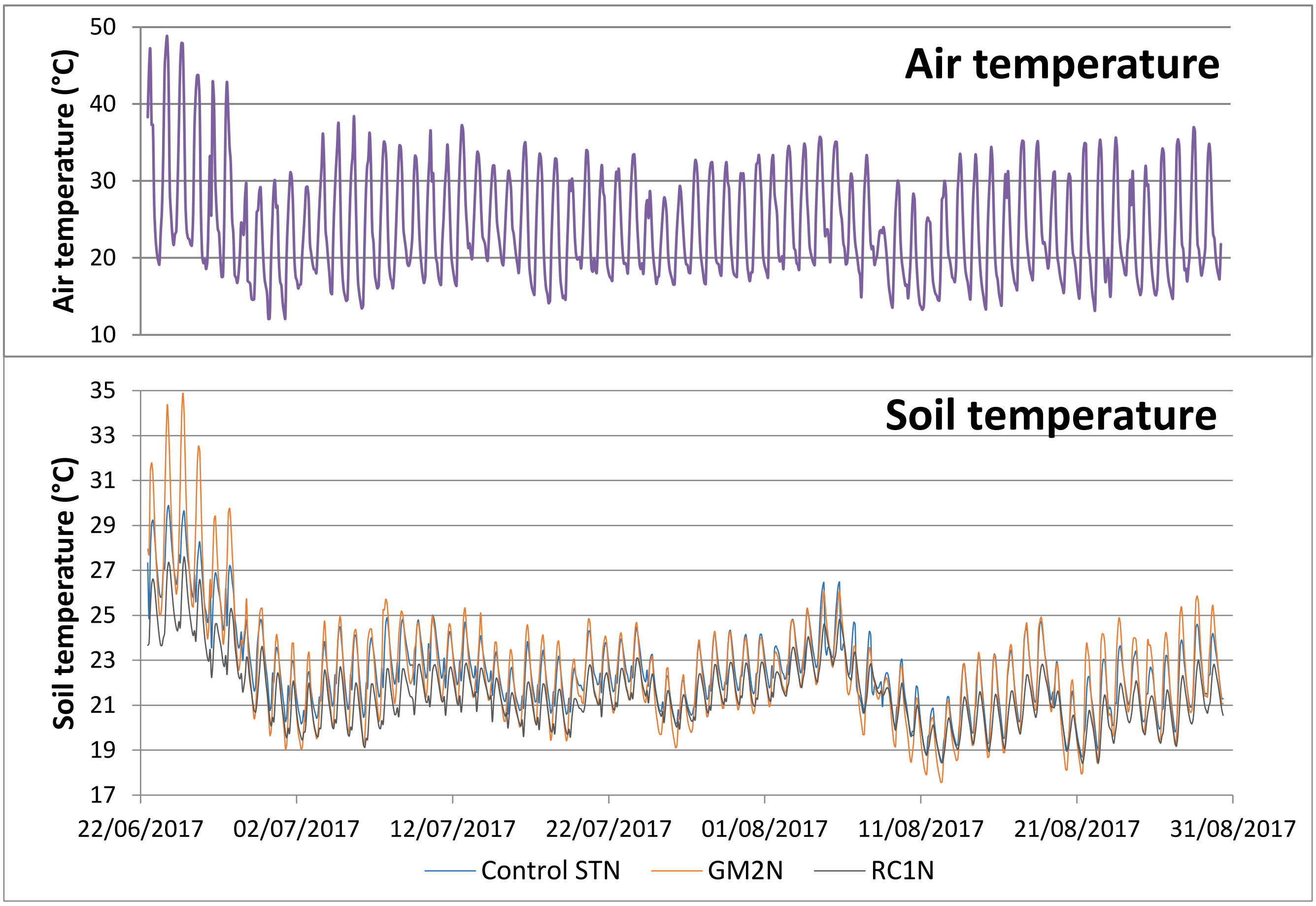


Figure 26: Soil temperature at 10cm depth measured every two hours during squash growth period on Control STS, GM2N and RC1N.

The soil was very humid and saturated in water (Figure 27). It indicated an excessive drip irrigation because moisture tension values at 30 and 45cm deep were very low. Quantities of water for irrigation were identical on all the plots due to the impossibility to make a differentiation between treatments. After 15/08/2017, when irrigation was reduced, more humidity variations were observed on GM1S than RC1N.

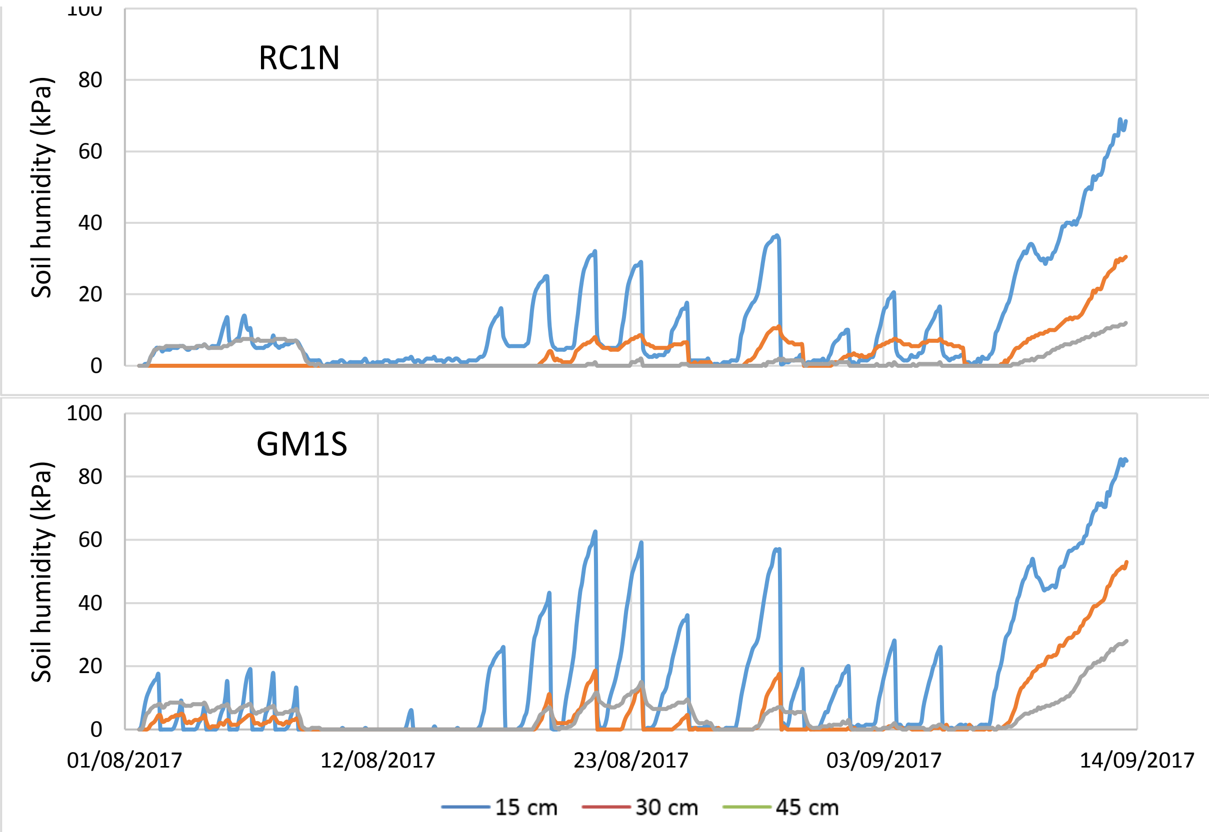


Figure 27: Soil humidity at the end of ASC cultivation on RC1N and GM1S at a depth of 15, 30 and 45 cm. Squash irrigation was stopped on 07/09/2017 before squash harvest.

4.4. Environment

Fuel consumption was between 188 and 197 L ha^{-1} on treatments with ASC (Figure 28). These values were higher than treatments without ASC because one passage of disc harrow and roller was done after soil slaking to sow the ASC. Soil tillage before squash transplantation consumed between 133 and 163 L ha^{-1}. Strip-tilled plots consumed only 6 to 7 L ha^{-1} of fuel. The four weeding operations on Control plots required also a high amount of fuel (194 L ha^{-1}). Thus, Tilled plots consumed more fuel than RC plots.

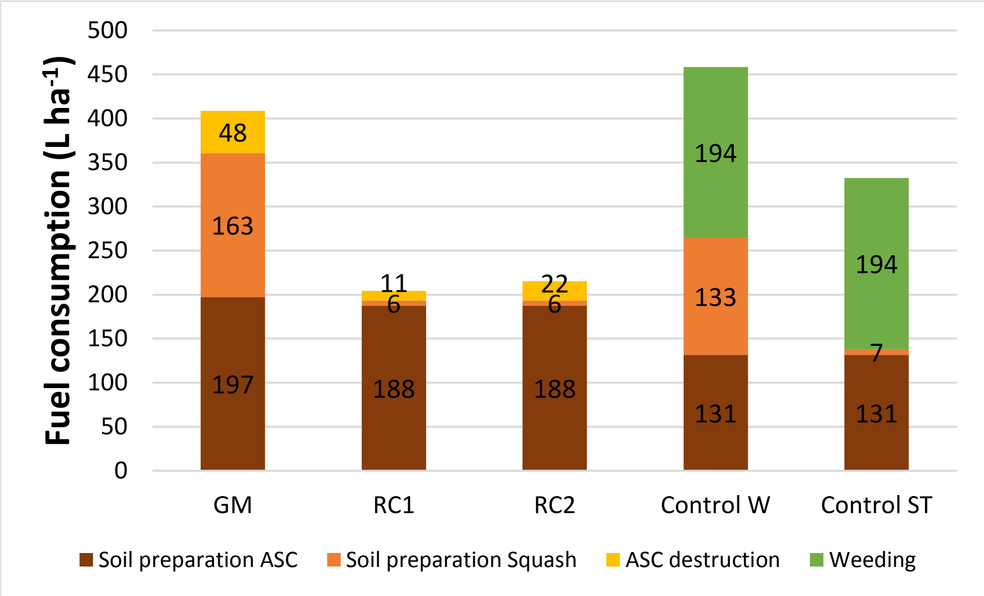


Figure 28: Fuel consumption for all the mechanical operations on the different treatments

4.5. Workload and economic profitability

4.5.1. Mechanical workload

Mechanical labour time spent was higher when soil was tilled (Figure 29). RC plots had a lower workload than GM and Control treatments. Control W required more time than GM since weeds were mowed four times (from March to May). Indeed, flail mowing is a slow operation (tractor's speed: 2.9 km h^{-1}). Control ST had also four weed mowings before squash transplantation. It explains the higher labour requirement for Control ST compared to RC treatments. ASC rolling was done at a faster speed (~12 km h^{-1}) compared to ASC mowing (~2.5 km h^{-1}). RC1 required slightly less work than RC2 (1.7 h ha^{-1}) because ASC2 was rolled two times. Mechanical workload followed approximately the same tendency as fuel consumption.

Total workload also includes manual operations such as weeding (see Figure 20 p. 39) or squash transplanting. It was not computed due to lack of timing data on irrigation, net setting and squash harvest.

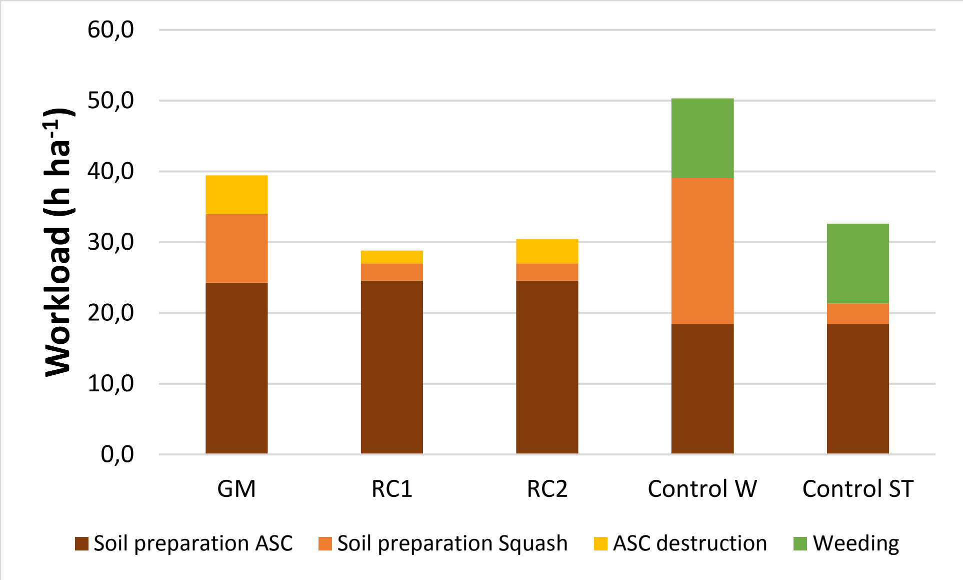


Figure 29: Workload for all the mechanical operations on the plot (weeding, planting and irrigation setting time were not included here)

4.5.2. Economical profitability

Turnover was higher in the tilled treatments compared to non-tilled treatments due to higher yields (Figure 30). With a medium butternut squash price of 1.20 € kg^{-1} (organic selling price in 2016), GM2 squash production generated a turnover of 40 915 € ha^{-1}. GM1 and Control W had a turnover of 38 628 € ha^{-1} and 37 973 € ha^{-1} respectively. RC1 had the lowest turnover (20 221 € ha^{-1}). RC2 produced a turnover of 25 397 € ha^{-1} and Control ST of 29 559 € ha^{-1}.

Differing costs are the costs that are not equivalent between treatments (weeding and mechanical workload, fuel consumption and ASC seeds). Other costs are equal for all treatments. Differing costs with no-till were less than half of costs on tilled plots. The main cost was weeding labour, which was higher in tilled treatments due to a higher number of weeds. The other costs were low compared to squash turnover. But overall, differing costs were very low compared to turnover, representing only 9.4 to 18.3 % of turnover.

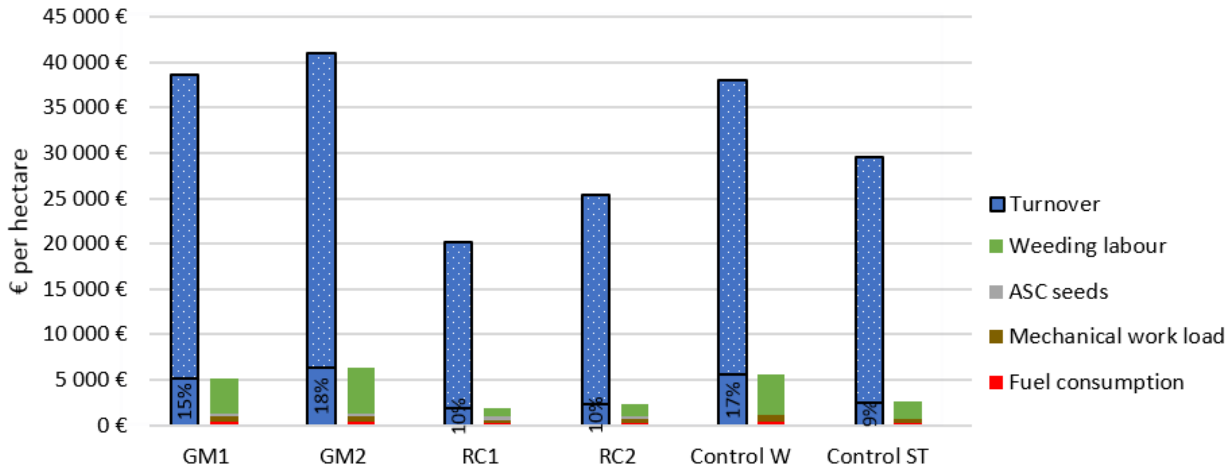


Figure 30: Turnover and differing costs (mechanical and weeding labour, ASC seeds and fuel consumption). Squash price = 1.20 € kg^{-1}; fuel price = 0.87 € L^{-1}; labour price = 13.86 € h^{-1}; ASC1 price = 328.6 € ha^{-1}; ASC2 price = 284 € ha^{-1}.

5. Discussion

The results obtained in the experiment provided answers to most of the hypotheses within the five sub-research questions raised in the introduction.

5.1. Is RC technique a good alternative to conventional production systems?

*** Agronomical performances (1)**

Low germination of rye in ASC1 (Figure 8) can be due to a low seed quality, or to soil slaking after the ASC sowing (high rainfall one day after sowing).

GM treatments were more vigorous than Control W at the beginning of Squash cycle, until the end of July, when Control W seemed more vigorous than GM (Figure 12). It could maybe explain why GM treatments had heavier squash than Control W. GM could have produced fruits earlier than Control W, having more time to fill compared to fruits on Control W.

ASC2 was not successfully terminated. It required two passages of roller-crimper and it was still not satisfactory. Fababean and barley needed to be terminated because it was nearly producing mature seeds. Fababean was easily terminated but the end of barley' stems straightened up. Then barley ears had time to mature, but they did not reseed, maybe thanks to pigeons that ate most of the grains on the barley's ears (Picture 11).

Picture 11: Barley ears eaten by pigeons

During the second passage of roller-crimper on RC2, most of the ASC residues were dried and the roller cut many stems of fababean and barley. Then ASC residues were not rooted anymore and could fly with the wind, decomposed quickly and attached the strip till that lead to stuffing. Thus, terminating ASC with only one rolling is more beneficial.

Rye represented more than 90% of ASC1 biomass and was successfully terminated with one passage of roller-crimper at late early dough stage (BBCH scale 83). No regrowth or lifting was observed and a thick mulch was produced.

Rye appeared easier to terminate compared to barley. However, rye had regrowth last year by straightening up because it was terminated too early, being more problematic than barley. Thus, the plant phenological stage seems to be the most important factor for a proper termination.

The trial confirmed the three key factors for a successful ASC termination already identified in bibliography, but ordered differently (part 2.3.):

1 Good timing: proper ASC growth stage
2 Good ASC species and varieties: synchronisation of the flowering stage
3 Good material (roller-crimper, strip till)

Few days after squash transplantation, some plants were damaged by slugs (*Arion rufus*, *Deroceras* spp. and *Milax* spp.) (Picture 12) and Mediterranean pine voles (*Microtus duodecimcostatus*) (Picture 13). Damages were mostly observed on RC plots. These plants were replaced and not included into the sampling plots.

Picture 12: Slug killed by Ferramol on RC1

Picture 13: Vole tumuli on RC1

The first infestation of powdery mildew (*Podosphaera xanthii* and/or *Golovinomyces cichoracearum var. cichoracearum*) was noticed on 02/08/2017. One week later, first symptoms of mosaic virus (cucumber mosaic virus and/or zucchini yellow mosaic virus) were observed at the end of young squash stems. On 08/08/2017, powdery mildew had an estimated intensity of 61% and 1.35 plants on 10 were infected by the virus on the sampling plots. No differences of infestation between the treatments were observed.

Slugs and voles seemed to be a specific problem of the ASC rolling. ASC mulch provided a habitat and shelter for voles and favoured topsoil moisture that attracts slugs. It required the trapping of voles and the use of Ferramol (iron phosphate) against slugs.

*** Weed control (2)**

RC technique seems to decrease weed development in the long term (Table 6). Indeed, weed density during ASC cultivation period was lower this year in ASC plots located on previous RC treatments (see map in Appendix 3). On 28/11/2017, Control East plot (previous RC1 and RC2) had a weed density five-times lower than Control West plot (previous GM3 and Control W). Some straw of previous ASC mulch was still on the soil surface on Control East plot. It was not the case on Control West plot. The same observation was done when comparing [GM1S&GM2N] (previous GM2 and GM1) with [GM1N&GM2S] (previous RC3), [GM1S&GM2N] having more weeds.

Two factors could explain a lower weed germination on previous RC treatments: the presence of cereal residues that could deter weed emergence and the allelopathic effect of ASC crop residues decomposition. Cereals might have an important allelopathic effect on the subsequent crop cultivated, especially for rye that has the strongest allelopathic potential among ASC species (Baldwin and Creamer, 2006).

During the squash cycle, RC technique clearly increased weed control compared to conventional systems (GM or Control W). This effect seems more due to reduced soil tillage (strip-tillage) than soil coverage by ASC mulch since Control ST (without ASC) had similar results than RC. This hypothesis needs to be nuanced since no rain came during squash cultivation. Thus, weed infestation was limited to irrigation lines. RC management also changed weed community compared to GM and Control W since less purslane was observed on RC than GM.

A lower weed density in the squash crop in GM1 compared to GM2 (Figure 19) agreed with a lower weeding labour (Figure 20) and could be explained by the higher biomass produced by ASC1 compared to AS2 and allelopathic potential of rye in ASC residues. All the species used as cover crops in the trial may have some allelopathic properties (Table 8). Among crops sown in ASC, cereals had a higher allelopathic potential since they produced a biomass and more effective allelochemical compounds. It coincides with the hypothesis already made above regarding rye potential allelopathic effect on weed growth at the beginning of ASC cycle.

Another hypothesis could have been that the higher soil nitrogen content on GM2 treatments compared to GM1 have promoted weed growth, but it was not verified with the soil nitrate measurements (Figures 21 and 22). But as mentioned in part 5.2.3., soil nitrate measurements done in this experiment were maybe not satisfactory to access real soil nitrogen content.

Table 8: Allelopathic properties of ASC species

Crop	**Allelopathic compounds**
Cereals	
Barley (*Hordeum vulgare* L.)	Scopoletin, Gramine, Hordenine, DIBOA[13], BOA[14] and DIMBOA[15] (Batish et al., 2001).
Rye (*Secale cereale* L.)	B-phenyllactic acid and B-hydroxybutitrc acid and various benzoxazolinone coumpounds (DIBOA, BOA, DIMBOA) (Batish et al., 2001).
Legumes	
Hairy vetch (*Vivia villosa* Roth.)	May have allelopathic properties with the production of the putative allelochemical cyanamide, but with a very low allelopathic potential compared to rye or wheat (Geddes et al., 2015).
Fababean (*Vicia faba* L.)	Have mentioned allelopathic properties, but there is a lack of information on the substances (Batish et al., 2001).
Forage pea (*Pisum sativum arvense* L.)	Has some allelopathic properties which come from the residues, but is not widely studied (Batish et al., 2001).

Purslane (*Portulaca oleracea*) presence on GM and Control W plots was predictable. It is an annual plant that is usually found in the south of France in warm conditions. It is often found on vegetable fields due to intensive soil tillage.

Among the weeds identified during ASC and squash cultivation, many were indicator plants. They suggested an excess of nitrogen fertilization, soil organic matter and irrigation (Table 9). Some were indicating an excess of irrigation and a compacted soil.

[13] DIBOA: 2,4-Dihydroxy-1,4(2H)-benzoxaxin-3-one
[14] BOA: 2(3H)-Benzoxazolinone
[15] DIMBOA : 2,4-dihydroxy-7-methoxy-1,4-benzoxazin-3-one

Table 9: Bio-indicator species in the experimental plot and characteristics (Ducerf and Thiry, 2003)

Indicator specie	Characteristics indicator
Capsella bursa pastoris	Important variations of soil humidity in loamy soils. Compacted soils. High nitrogen content.
Convolvulus arvensis	Clay-humic complex saturation in nitrogen. Excess of organic matter. Nitrophilous spp.
Echinochloa crus-galli	Organic matter, nitrogen and potash excess. Mediterranean region. Excess in irrigation.
Lamium amplexicaule	Excess in nitrogen. Soil rich in organic matter.
Picris hieracioides	Compacted soil. High pH, bases content and hydric contrasts. Anaerobic conditions
Senecio vulgaris	Nitrogen excess or organic matter. Lack of soil coverage.
Stelaria media	High level of organic matter with intense microbial life
Sonchus spp.	Excess in N, MO, too much irrigation, K
Veronica persica	Excess with bases. Excess of nitrogen and high level of organic matter. Start of anaerobic conditions. Nitrophilous spp.

*** Soil quality and fertility (3)**

It is important to remember the specific soil conditions on the experimental plot. The experimental field soil is a clay loam, very susceptible to compaction. It is not an ideal soil for no-tillage technique (Peigné et al., 2007). It explains the differences in bulk density between tilled and strip-tilled treatments (Figures 24 and 25). The soil was more compacted when soil was not tilled due to a tendency of soil for self-compaction. This was probably accentuated by excessive irrigation. Thus, soil dioxygen gas content was lower, decreasing nitrogen dynamics and creating soil asphyxia because of the excess of water. This difference of squash rooting certainly explains the differences of growth and yield between tilled treatments and strip-tilled ones. Thus, the hypothesis that RC would improve soil structure and decrease soil compaction was not verified.

RC maintained more soil moisture compared to GM management, even if the differences in soil moisture measured were not high. RC also buffered soil temperature compared to GM treatment.

*** Environment (4)**

RC is more sustainable for the environment than GM because it consumed twice less fuel than GM, thus limiting GHG emissions. Reduced soil tillage highly decreased tractor fuel consumption.

*** Workload and economical profitability (5)**

The hypothesis that RC could reach the same economic performance than conventional systems was not verified. RC had a significantly lower turnover than GM and Control W. Even if changing costs were lower for RC management (explained by less mechanical and weeding labour), it did not compensate a much lower yield compared to conventional systems.

5.2. Critical analysis

5.2.1. Experimental design

Integration of Control ST treatment in the trial was an asset since it clearly showed that soil tillage explained most of the differences between RC and GM management techniques, in terms of soil compaction and porosity, weed density and squash nutrition and agronomical performances.

Last year experimental design has improved since more repetitions were made for the GM and Control treatments. Randomly assigning the treatments within the block could have been an improvement from a statistical point of view, but was difficult since ASC on RC needed a complete row to be rolled.

The treatments were not exactly on the same rows as last year's treatments (see map in Appendix 3). This was an experimental weak point because it was difficult to interpret the influence of previous soil tillage management practices on subsequent year treatments.

5.2.2. Technical system management

In both ASC, pea did not develop well, even if it had a correct germination rate and growth the first month (Figures 8, 9 and 10). Available nitrogen before ASC establishment was maybe too high, disadvantaging the development of pea, contrary to cereals (White et al., 2016). Also, cereals seeding rate was maybe too high compared to pea and vetch. It would be interesting to test the same ASC mixture without previous fertilisation and to reduce cereals sowing density in ASC mixtures to study if pea develops better.

The hypothesis that roller-crimper weight was to light and used at too high speed was made. Roller crimping operation of ASC2 was done at a mean speed of 15 km h^{-1} and with a roller weight of 410 kg per linear meter. Roller-crimper weights on the market are situated between 400 and 800 kg per linear meter and can often be filled with water to increase weight (Appendix 11). Also, according to Labreuche and Kornecki (2017, personal email communication, 26 and 27 April), the rolling speed used was too high. In his email, Kornecki (2017, personal communication, 27 April) suggested a maximum speed of 12km/h and proposes to increase the weight of the roller-crimper. Indeed, he said that "at higher speed, the mass of inertia of the roller lessens the effects of gravitational downward force". These information can be taken into account for subsequent ASC rolling, trying to decrease the speed of rolling and add more weights.

Irrigation was an issue during this trial. The soil was more humid in the south compared to north treatments, and also less humid in the west part. It could be explained by the presence of hedges on west and north part of the experimental trial (see map in Appendix 4). It seems also that drip irrigation system did not water the field uniformly. Moreover, RC treatments would have required less irrigation than other treatments, but it was not feasible due to irrigation set. It could have induced nitrate leaching. This could be improved for future experimentation.

Squash transplantation required two times more workload on strip-tilled plots than tilled plots because the soil was very dry and lumpy. Squash could have been transplanted in mud after drip irrigation to reduce workload.

5.2.3. Measurements protocol

ASC1 biomass measurement was done on 13/04/2017, at the same time as ASC2, but ASC1 was rolled only one month later (16/05/2017). Real total ASC1 biomass is probably above 15

Mg ha^{-1}, because rye was two-meter-high when it was terminated and provided a very thick mulch compared to ASC2.

At the end of ASC cultivation, when ASC were sampled to assess biomass produced, most of the weeds were dried and many were already decomposing on the soil. However, some *Sonchus* spp. were still fresh in the harvested biomass. These two points could explain the non-significant results presented in Figure 18 that did not reflect the real weed density one month before.

Nitrate (NO_3^-) measurements presented in Figure 21 and Figure 22 only take into account one form of nitrogen. Maybe other forms of nitrogen (mineral or gaseous N) would explain the squash nitrogen nutrition differences between treatments. During squash cultivation cycle, denitrification was probably favoured by anaerobic soil conditions, which was directly linked with a water saturated soil (Weil and N. C., 2017). N volatilization may also have happened on top soil since soil pH was alkaline and evaporation was favoured by warm temperatures and windy conditions (Weil and N. C., 2017). Thus, the measurement of total mineral nitrogen (nitrate, nitrite, ammonium) and gaseous nitrogen losses (ammonia, nitric oxide, nitrous oxide gas and dinitrogen gas) would be more appropriate to see differences between treatments.

Fuel consumption on Control plots could be lower for a producer than the values presented in Figure 28. In the experiment, it was a choice to mow weeds four times to try to keep a bare soil and to avoid weed to take nutrients from the soil. A producer will only mow weed ones. Also, the soil was tilled on Control plot even if no ASC was sown. Thus, RC treatments could have consumed more fuel than Control W. ASC implantation is required a high amount of fuel for soil tillage. Maybe sowing of ASC without soil tillage could be a solution to reduce fuel consumption and GHG emissions.

Costs computed on Figure 30 only consider changing costs between treatments. It could have been interesting to compute real gross margin for each management technique to be able to compare these values with references.

5.3. Implications and outlooks

Lower yields on RC compared to GM treatments were also measured last year. The hypothesis was that difference of nitrogen fertilisation between RC and GM was the main reason. The results obtained this year show that the soil structure (lower soil porosity and increased soil compaction) impacted more squash yield than fertilisation. But yields were higher on all treatments, probably because of fertilisation before ASC sowing, better weeding management and warmer condition during squash crop cycle. Weed control was also better on RC last year compared to GM treatments. The conclusion that soil tillage was the main factor to explain differences in soil structure and weed development can be made thanks to Control ST treatments which had similar results as RC treatments.

RC technique did not produce expected results regarding soil structure and quality as well as agronomical squash performances and economic profitability. However, it is important to mention that these results are specific to the pedoclimatic condition of the experiment. Loam clay soil of the experimental plot was not the most suitable soil texture for reduced tillage technique. Indeed, it has a tendency for auto-compaction and clacking crust formation. The warm climate in summer with low rainfalls (Mediterranean climate) did not promote weed growth to see significant differences between Control ST and RC treatments for the ASC mulch weed control effect. Also, results were obtained in short-term experiment. As mentioned by many defenders of no-tillage, several years of no-tillage are needed to see a positive effect on soil structure. Doing the experiment during more than four years without tilling soil before ASC sowing could be interesting to see if the expected benefits on soil are seen. The results of Soilveg project will be interesting to see results of the same experiment done in different pedoclimatic conditions with other cash crop species.

It would have been interesting to evaluate consequences of RC technique on other indicators:

- RC increases soil biodiversity
- RC is promoting survival of beneficial insects providing them a permanent habitat/shelter and food (pollen, insects, …) (some partners of Soilveg project are working on it)
- More biodiversity can be observed on GM and RC compared to bare soil (e.g. Pollinators and beneficial insects)
- RC and GM requires less fertilisation than bare soil on the long-term

Even if the technique is optimized in future, it will certainly not be adapted for all production and all pedo-climatic conditions. RC technique is reducing cash crop precocity due to lower soil temperature and slower nitrogen mineralisation. Therefore, RC technique cannot be used for spring vegetables species due to earliness. Earliness problems were minimized in this trial due to very warm conditions, high sunshine and overall because precocity is not an intended goal for squash production since it is a winter consumption product. Therefore, RC technique could be suitable if optimized for specific vegetable cropping systems on specific production sites.

Other kinds of solutions than rolled winter cover crop could be considered to increase agroecosystem sustainability while remaining in the conservation agriculture principles and overcoming the problem of short time availability in vegetable production to cultivate cover crops (Pousset, 2000). Cover crops could be cultivated on other plots, harvested and mulched on the cultivated plot. Using a perennial crop could be a solution to produce green manure biomass during a long period (with alfalfa for example). Cover crop can also be cultivated within the cash crop as living mulch, as it is sometimes done with clover. An alternative solution to rolling to terminate completely the cover crop, is to shade it with a thick plastic mulch, but it is only feasible on small surfaces due to high expenses and time demand.

6. Conclusion

The rolling technique to properly terminate an ASC proved feasible, even in organic farming conditions without any herbicide. Indeed, rye was successfully terminated in ASC1 mixture. RC technique was a good alternative compared to conventional management systems (GM or Control W management) for weed control. However, it did not improve soil structure and quality in the short term. The soil was more compacted with a lower porosity than tilled soils, potentially reducing soil nitrogen mineralisation. Squash roots were shallower on RC treatments. Squash agronomical performances were lower on RC treatments, impacting strongly economical performances which were clearly lower.

Thus, the technique of winter ASC rolled did not appear as a good alternative to conventional systems with the agronomical choices made (ASC choice, crop fertilisation, weeding management, etc.) within pedoclimatic conditions of the experiment. Redoing this research without soil tillage on a long-term experiment (> 4 years) would be interesting to study if the soil quality and fertility is improving with RC management.

Bibliography

Agence Bio, 2017. La bio change d'échelle en préservant ses fondamentaux [WWW Document]. URL http://www.agencebio.org/sites/default/files/upload/AgoraBIO/dp_bio_barometre_val.pdf (accessed 4.25.17).

Altieri, M.A., Lana, M.A., Bittencourt, H.V., Kieling, A.S., Comin, J.J., Lovato, P.E., 2011. Enhancing Crop Productivity via Weed Suppression in Organic No-Till Cropping Systems in Santa Catarina, Brazil. J. Sustain. Agric. 35, 855–869. doi:10.1080/10440046.2011.588998

Ashford, D.L., Reeves, D.W., 2003. Use of a mechanical roller-crimper as an alternative kill method for cover crops. Am. J. Altern. Agric. 18, 37–45.

Atelier Paysan, 2016. Projet Buzuk - 2ème année.

Atelier Paysan, n.d. Rolo FACA (GRAB) [WWW Document]. L'Atelier Paysan. URL http://www.latelierpaysan.org/Rolo-FACA (accessed 3.22.17).

Baldwin, K.R., Creamer, N.G., 2006. Cover crops for organic farms. N. C. Coop. Ext. Serv. Raleigh NC.

Balkcom, K., Schomberg, H., Reeves, W., Clark, A., Baumhardt, L., Collins, H., Delgado, J., Duiker, S., Kaspar, T., Mitchell, J., 2007. Managing cover crops in conservation tillage systems. Manag. Cover Crops Profitab. 44–61.

Bàrberi, P., 2002. Weed management in organic agriculture: are we addressing the right issues? Weed Res. 42, 177–193.

Batish, D.R., Singh, H.P., Kaur, S., 2001. Crop Allelopathy and Its Role in Ecological Agriculture. J. Crop Prod. 4, 121–161. doi:10.1300/J144v04n02_03

Bleiholder, H., Weber, E., Lancashire, P.D., Feller, C., Buhr, L., Hess, M., Wicke, H., Hack, H., Meier, U., Klose, R., others, 2001. Growth stages of mono-and dicotyledonous plants, BBCH monograph. Fed. Biol. Res. Cent. Agric. For. BerlinBraunschweig Ger. 158.

Buchanan, A.L., Kolb, L.N., Hooks, C.R.R., 2016. Can winter cover crops influence weed density and diversity in a reduced tillage vegetable system? Crop Prot. 90, 9–16. doi:10.1016/j.cropro.2016.08.006

Butler, D.M., Bates, G.E., Inwood, S.E.E., 2016. Tillage System and Cover Crop Management Impacts on Soil Quality and Vegetable Crop Performance in Organically Managed Production in Tennessee. HortScience 51, 1038–1044.

Canali, S., Campanelli, G., Ciaccia, C., Leteo, F., Testani, E., Montemurro, F., 2013. Conservation tillage strategy based on the roller crimper technology for weed control in Mediterranean vegetable organic cropping systems. Eur. J. Agron. 50, 11–18. doi:10.1016/j.eja.2013.05.001

Canali, S., Diacono, M., Campanelli, G., Montemurro, F., 2015. Organic No-Till with Roller Crimpers: Agro-ecosystem Services and Applications in Organic Mediterranean Vegetable Productions. Sustain. Agric. Res. 4, 70. doi:10.5539/sar.v4n3p70

Carr, P.M., Mäder, P., Creamer, N.G., Beeby, J.S., 2012. Editorial: Overview and comparison of conservation tillage practices and organic farming in Europe and North America. Renew. Agric. Food Syst. 27, 2–6. doi:10.1017/S1742170511000536

Clark, A., 2008. Managing Cover Crops Profitably (3rd Ed.). DIANE Publishing.

Creamer, N.G., Bennett, M.A., Stinner, B.R., 1997. Evaluation of Cover Crop Mixtures for Use in Vegetable Production Systems. HortScience 32, 866–870.

Dabney, S.M., Delgado, J.A., Reeves, D.W., 2001. Using Winter Cover Crops to Improve Soil and Water Quality. Commun. Soil Sci. Plant Anal. 32, 1221–1250. doi:10.1081/CSS-100104110

Delate, K., Cwach, D., Chase, C., 2012. Organic no-tillage system effects on soybean, corn and irrigated tomato production and economic performance in Iowa, USA. Renew. Agric. Food Syst. 27, 49–59. doi:10.1017/S1742170511000524

Derpsch, R., 2001. Keynote: Frontiers in conservation tillage and advances in conservation practice, in: Stott DE, Mo Htar, RH, and Steinhart G. C (Eds.) Sustaining the Global Farm. Selected Papers from the 10th International Soil Conservation Organisation Meeting Held May. pp. 24–29.

Ducerf, G., Thiry, C., 2003. Les plantes bio-indicatrices. : Guide de diagnostic des sols. Editions Promonature, Briant (Saône-et-Loire).

FAO, 2008. Investing in Sustainable Crop Intensification: The Case for Soil Health. Report of the International Technical Workshop, in: Integrated Crop Management. Rome.

FAO, 1999. Organic agriculture, in: Committee on Agriculture. Presented at the Fifteenth Session, Rome.

Feeser, J., Zinati, G., Moyer, J., 2014. Beyond Black Plastic: cover-crops and organic no-till for vegetable production. Rodale Inst. Ed.

Fiedler, L., 2016. Analysis of an organic vegetable cropping system following conservation agriculture principles (in French) (MSc thesis). Avignon University, France.

Geddes, C., Cavalieri, A., Daayf, F., Gulden, R., 2015. The Allelopathic Potential of Hairy Vetch (Vicia villosa Roth.) Mulch. Am. J. Plant Sci. 06, 2651–2663. doi:10.4236/ajps.2015.616267

Halde, C., Bamford, K.C., Entz, M.H., 2015. Crop agronomic performance under a six-year continuous organic no-till system and other tilled and conventionally-managed systems in the northern Great Plains of Canada. Agric. Ecosyst. Environ. 213, 121–130. doi:10.1016/j.agee.2015.07.029

Hartwig, N.L., Ammon, H.U., 2002. Cover crops and living mulches. Weed Sci. 50, 688–699.

Hummel, R.L., Walgenbach, J.F., Hoyt, G.D., Kennedy, G.G., 2002. Effects of production system on vegetable arthropods and their natural enemies. Agric. Ecosyst. Environ. 93, 165–176. doi:10.1016/S0167-8809(01)00345-0

IFOAM, 2005. Definition of Organic Agriculture [WWW Document]. URL http://www.ifoam.bio/en/organic-landmarks/definition-organic-agriculture (accessed 5.30.17).

Jackson, M., Harrison, H., 2008. Effects of a Killed-Cover Crop Mulching System on Sweetpotato Production, Soil Pests, and Insect Predators in South Carolina [WWW Document]. URL https://naldc.nal.usda.gov/download/22153/PDF (accessed 3.27.17).

Jokela, D., Nair, A., 2016. No Tillage and Strip Tillage Effects on Plant Performance, Weed Suppression, and Profitability in Transitional Organic Broccoli Production. HortScience 51, 1103–1110. doi:10.21273/HORTSCI10706-16

Kornecki, T.S., 2016. The Effects of Combined Cover Crop Termination and Planting in a Cotton No-Till System. Appl. Eng. Agric. 32, 551–560. doi:10.13031/aea.32.11568

Kornecki, T.S., Arriaga, F.J., Price, A.J., 2012. Roller type and operating speed effects on rye termination rates, soil moisture, and yield of sweet corn in a no-till system. HortScience 47, 217–223.

Kornecki, T.S., Price, A.J., Raper, R.L., Arriaga, F.J., 2009. New roller crimper concepts for mechanical termination of cover crops in conservation agriculture. Renew. Agric. Food Syst. 24, 165–173. doi:10.1017/S1742170509002580

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World Map of the Köppen-Geiger climate classification updated. Meteorol. Z. 15, 259–263. doi:10.1127/0941-2948/2006/0130

Lamont, W.J., 2005. Plastics: modifying the microclimate for the production fo vegetable crops. HortTechnology.
Leavitt, M.J., Sheaffer, C.C., Wyse, D.L., Allan, D.L., 2011. Rolled winter rye and hairy vetch cover crops lower weed density but reduce vegetable yields in no-tillage organic production. HortScience 46, 387–395.
Lowry, C.J., Brainard, D.C., 2016. Strip-Intercropping of Rye–Vetch Mixtures Affects Biomass, Carbon/Nitrogen Ratio, and Spatial Distribution of Cover Crop Residue. Agron. J. 108, 2433. doi:10.2134/agronj2016.04.0189
Luna, J.M., Mitchell, J.P., Shrestha, A., 2012. Conservation tillage for organic agriculture: Evolution toward hybrid systems in the western USA. Renew. Agric. Food Syst. 27, 21–30. doi:10.1017/S1742170511000494
Mirsky, S.B., Curran, W.S., Mortensen, D.A., Ryan, M.R., Shumway, D.L., 2009. Control of Cereal Rye with a Roller/Crimper as Influenced by Cover Crop Phenology. Agron. J. 101, 1589. doi:10.2134/agronj2009.0130
Mohrmann, E., 2016. MSc. Internship experimental synthesis report. Cover crop experimentation with the Groupe de Recherche en Agriculture Biologique (GRAB) in Avignon, France. Wageningen University.
Montemurro, F., Fiore, A., Campanelli, G., Tittarelli, F., Ledda, L., Canali, S., 2013. Organic fertilization, green manure, and vetch mulch to improve organic zucchini yield and quality. HortScience 48, 1027–1033.
Morse, R.D., 1999. No-till vegetable production—its time is now. HortTechnology 9, 373–379.
Morse, R.D., 1995. No-till, no-herbicide systems for production of transplanted broccoli. WL Kingery N Buehring Conserv. Farming Focus Water Qual. Proc South. Reg Conserv. Tillage Sustain. Agr Jackson Miss 26–28.
ORAB PACA, 2016. L’agriculture biologique en Provence Alpes Côte d’Azur - Edition 2016. Observatoire Régionale Régional de l’Agriculture Biologique en région PACA.
OSCAR project team, 2016. Project Final report : OSCAR - Optimising Subsidiary Crop Application in Rotations.
Overstreet, L.F., Hoyt, G.D., Imbriani, J., 2010. Comparing nematode and earthworm communities under combinations of conventional and conservation vegetable production practices. Soil Tillage Res. 110, 42–50. doi:10.1016/j.still.2010.06.009
Parr, M., Grossman, J.M., Reberg-Horton, S.C., Brinton, C., Crozier, C., 2011. Nitrogen Delivery from Legume Cover Crops in No-Till Organic Corn Production. Agron. J. 103, 1578. doi:10.2134/agronj2011.0007
Peigné, J., Ball, B.C., Roger-Estrade, J., David, C., 2007. Is conservation tillage suitable for organic farming? A review. Soil Use Manag. 23, 129–144. doi:10.1111/j.1475-2743.2006.00082.x
Peigné, J., Casagrande, M., Payet, V., David, C., Sans, F.X., Blanco-Moreno, J.M., Cooper, J., Gascoyne, K., Antichi, D., Bàrberi, P., Bigongiali, F., Surböck, A., Kranzler, A., Beeckman, A., Willekens, K., Luik, A., Matt, D., Grosse, M., Heß, J., Clerc, M., Dierauer, H., Mäder, P., 2015. How organic farmers practice conservation agriculture in Europe. Renew. Agric. Food Syst. 31, 72–85. doi:10.1017/S1742170514000477
Pousset, J., 2000. Engrais verts et Fertilité des sols, Edition Agridécisions. ed. Paris.
Price, A.J., Norsworthy, J.K., 2013. Cover Crops for Weed Management in Southern Reduced-Tillage Vegetable Cropping Systems. Weed Technol. 27, 212–217. doi:10.1614/WT-D-12-00056.1
Raper, R.L., Simionescu, P.A., Kornecki, T.S., Price, A.J., Reeves, D.W., 2004. Reducing vibration while maintaining efficacy of rollers to terminate cover crops. Appl. Eng. Agric. 20, 581–584. doi:10.13031/2013.17458

Raynal Lacroix, C., Abarza, E., 2002. PILazo: une méthode de gestion raisonnnée de l'azote. Info-Ctifl N°180 36–39.
Reberg-Horton, S.C., Grossman, J.M., Kornecki, T.S., Meijer, A.D., Price, A.J., Place, G.T., Webster, T.M., 2012. Utilizing cover crop mulches to reduce tillage in organic systems in the southeastern USA. Renew. Agric. Food Syst. 27, 41–48. doi:10.1017/S1742170511000469
Shirtliffe, S.J., Johnson, E.N., 2012. Progress towards no-till organic weed control in western Canada. Renew. Agric. Food Syst. 27, 60–67. doi:10.1017/S1742170511000500
Smith, A.N., Reberg-Horton, S.C., Place, G.T., Meijer, A.D., Arellano, C., Mueller, J.P., 2011. Rolled Rye Mulch for Weed Suppression in Organic No-Tillage Soybeans. Weed Sci. 59, 224–231. doi:10.1614/WS-D-10-00112.1
SoCo Project Team, 2009. Final report on the project "Sustainable Agriculture and Soil Conservation (SoCo)." European Communities.
Teasdale, J.R., Beste, C.E., Potts, W.E., 1991. Response of weeds to tillage and cover crop residue. Weed Sci. 195–199.
The R Foundation for Statistical Computing, 2017. R version 3.4.0 -- "You Stupid Darkness". Copyright (C) 2017. Computing Platform: x86_64-w64-mingw32/x64 (64-bit).
Tillman, J., Nair, A., Gleason, M., Batzer, J., 2015. Rowcovers and Strip Tillage Provide an Alternative to Plasticulture Systems in Summer Squash Production. HortScience 50, 1777–1783.
Toussaint, V., Ciotola, M., 2015. Impact des cultures de couverture sur les maladies des cucurbitacées. Agric. Agri-Food Can.
Treadwell, D.D., Creamer, N.G., Hoyt, G.D., Schultheis, J.R., 2008. Nutrient management with cover crops and compost affects development and yield in organically managed sweetpotato systems. HortScience 43, 1423–1433.
Treadwell, D.D., Creamer, N.G., Schultheis, J.R., Hoyt, G.D., 2007. Cover Crop Management Affects Weeds and Yield in Organically Managed Sweetpotato Systems. Weed Technol. 21, 1039–1048. doi:10.1614/WT-07-005.1
Triplett, G.B., Dick, W.A., 2008. No-Tillage Crop Production: A Revolution in Agriculture! Agron. J. 100, S-153. doi:10.2134/agronj2007.0005c
Védie, H., Métais, P., 2013. Soil working practices, machinery used and innovation in vegetable production (organic): surveys in South-East of France (in French). Dossier pratiques de travail du sol : Enquêtes dans le Sud-Est., Maraîchage Bio Infos n°77 – 3ème trimestre. GRAB, Avignon, France.
Vollmer, E.R., Creamer, N., Reberg-Horton, C., Hoyt, G., 2010. Evaluating cover crop mulches for no-till organic production of onions. HortScience 45, 61–70.
Wayman, S., Cogger, C., Benedict, C., Burke, I., Collins, D., Bary, A., 2015. The influence of cover crop variety, termination timing and termination method on mulch, weed cover and soil nitrate in reduced-tillage organic systems. Renew. Agric. Food Syst. 30, 450–460. doi:10.1017/S1742170514000246
Weil, R., N. C., B., 2017. Nitrogen and Sulfur Economy of Soils. p. 584–642. doi:10.13140/RG.2.1.1435.0482
Wells, M.S., Reberg-Horton, S.C., Smith, A.N., Grossman, J.M., 2013. The Reduction of Plant-Available Nitrogen by Cover Crop Mulches and Subsequent Effects on Soybean Performance and Weed Interference. Agron. J. 105, 539. doi:10.2134/agronj2012.0396
Wetselaar, R., Smith, G.D., Angus, J.F., 1998. Field measurement of soil nitrate concentrations. Commun. Soil Sci. Plant Anal. 29, 729–739.

White, C.A., Holmes, H.F., Morris, N.L., Stobart, R.M., 2016. A review of the benefits, optimal crop management practices and knowledge gaps associated with the different cover crop species. Research Review No. 90.

Wortman, S.E., Francis, C.A., Lindquist, J.L., 2012. Cover Crop Mixtures for the Western Corn Belt: Opportunities for Increased Productivity and Stability. Agron. J. 104, 699. doi:10.2134/agronj2011.0422

Appendices

Appendix 1: Terminology of technical terms related to the study

Technical term	**Synonymous or refer to**
Agroecological Service Crops (ASC)	Catch crops, complementary crops, cover crops, green manure, living mulches, break crops, buffer zones, subsidiary crops
Conservation tillage	No-till system, minimum tillage, reduced tillage, simplified cultural technique, direct seeding, strip-till system, mulch based crop system, living mulch, rolled cover-crop
Conventional tillage	Inversion ploughing, mouldboard plough, deep soil tillage, soil tillage (>20cm), soil disturbance, soil tillage
Roller-crimper	"Rolo faca" (Portuguese name which is often used because the technique originates from Brazil), roller-chopper, knife roller, blade roller
Soil tillage	Ploughing, sub-soiling or harrowing with tined tools, rotating tools, cultivator (rotatory or stubble), rototiller/tiller, harrow (spiked or rotary), stone burier, etc.

From: (Altieri et al., 2011; Ashford and Reeves, 2003; Canali et al., 2015; Peigné et al., 2015, 2007)

Appendix 2: Cash crop species better adapted to RC technology

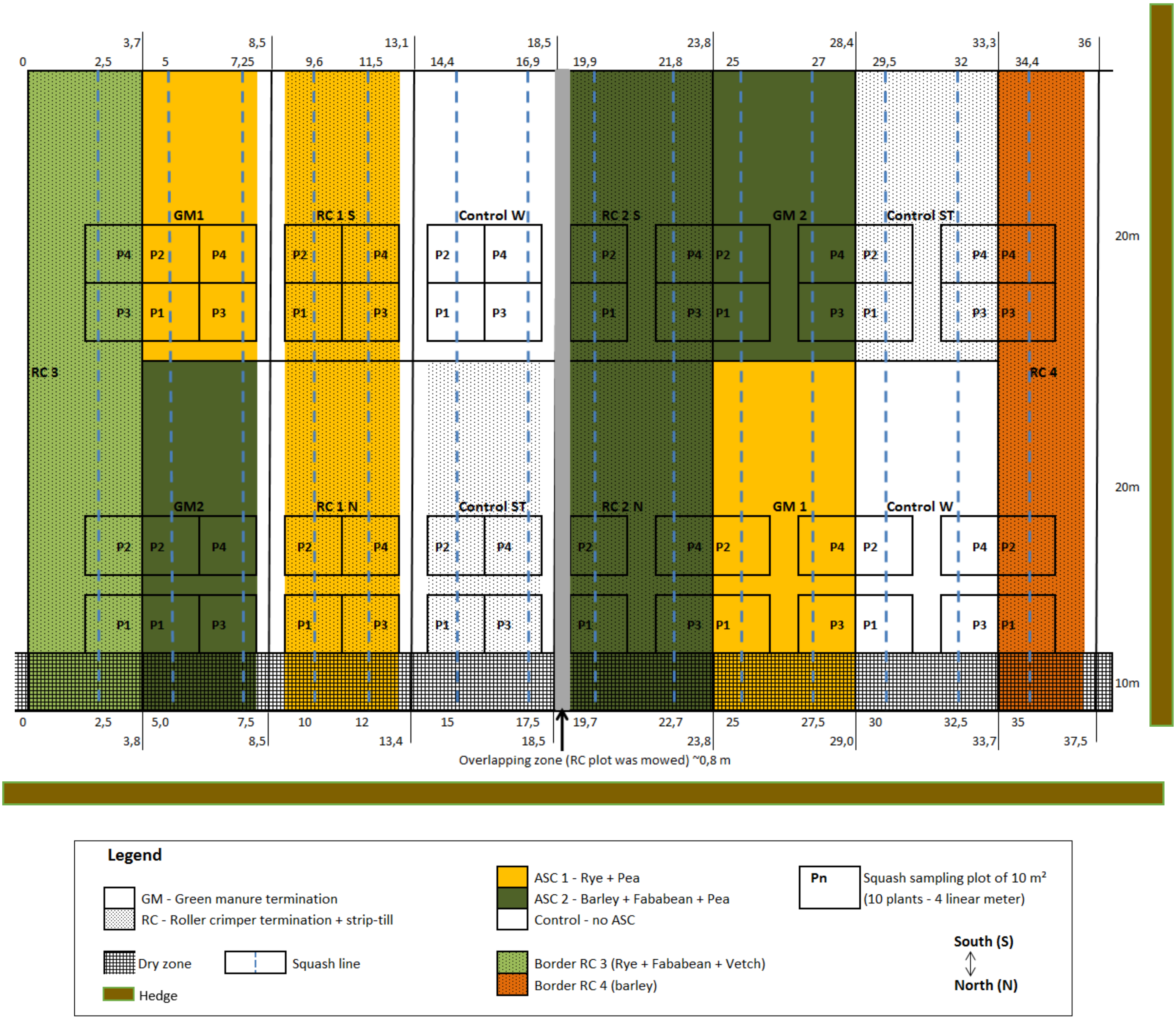
Vegetable specie	Adapted specie?*	Description	Source
Broccoli [Brassica oleracea L.]	YES	No yield differences between GM and RC in 2015. GM yielded 31% more than RC in 2014 (cover crop: rye and hairy vetch). Viable for organic vegetable growers.	(Jokela and Nair, 2016)
Eggplant [Solanum melongena L.]	YES	No significant yield differences between RC, GM and Control (cover crop: wheat and crimson clover). Problem of cover crop destruction and delay in planting. 80% lower yield in RC compared to plastic mulch system.	(Butler et al., 2016) (Luna et al., 2012)
Melon [Cucumis melo L.]	YES	Similar yields between RC, GM and Control. Differences were observed depending on the fertilisation. With no fertilisation, RC produced less than GM and Control.	(Canali et al., 2015)
Onion [Allium cepa L.]	YES	No significant yield differences between RC and bare soil (cover crop: foxtail millet, cowpea, foxtail millet and cowpea)	(Vollmer et al., 2010)
Sweetpotatoes [Ipomoea batatas (L.)]	YES	Over 3 years: similar yields 2 years between RC, GM and Control, and lower yield for RC only one year due to high weed pressure.	(Treadwell et al., 2007)
Tomato [Lycopersicon esculentum Mill.]	YES	No significant difference between RC, GM and plastic mulch. 40% Less damaged fruits in RC (cover crop: hairy vetch). Depends on the year. GM>RC>Plastic mulch in 2010. Plastic>>GM&RC in 2011 (cover crop: rye; hairy vetch; rye and hairy vetch).	(Canali et al., 2015) (Feeser et al., 2014)
Watermelon [Citrullus lanatus]	?	Lower watermelon yield in RC than GM and Tilled bare soil, but no significant statistical difference. More weeds than eggplant plots (cover crop: wheat and crimson clover).	(Butler et al., 2016)
Zucchini [Cucurbita pepo L.]	YES	RC yielded 69% more than GM and 25% more than control (cover crop: barley). 20% less yield in RC compared to GM with rye ASC. But yield difference was not significant.	(Canali et al., 2015) (Luna et al., 2012)

* Adapted cash crop species after rolling an ASC. "Yes": the technique is well suited in comparison with GM or Control. "?": research results are not conclusive.

Appendix 3: Experimental design FtA trial in 2015-2016 and 2016-2017

Appendix 4: Experimental design during squash cultivation with sampling plots

We delimitated four sampling plots on each experimental plot, two on each squash transplantation line (East and West). Each sampling plot gathered ten squash plants, representing 10 m² (2.5m x 4m). These plots served as repetition for observations and measurements on the squash crop.



Appendix 5: Machinery characteristics and fuel consumption

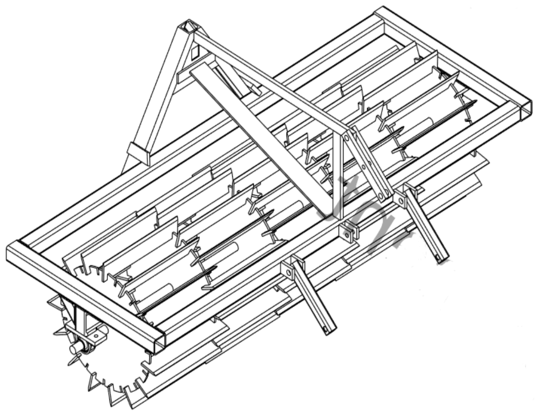
Equipment	**Machine details**	**Fuel consumption ($L.ha^{-1}$) ***	**Fuel consumption ($L.h^{-1}$) ***	**Working width (m)**	**Picture**
Tractor	Class 220 VL Nexos (85 horsepower)				
Flail mower	FALCONERO, model TIGRE175 (2011) Italy	44,44	8,80	1,8	
Rotary harrow (15cm deep)	CELLI S.p.A., model 60 200 (2006) Italy	37,93	12,97	2,0	
Cultivator (15cm deep)	GARD Potelières, model Z130 (1979) France	33,33	17,14	2,0	
Subsoiler (30cm deep)	HOWARD, model Paraplow - 1200 (1995) France	23,81	6,84	2,0	
Disk harrow (15cm deep)	Goizin, model ? (?) France	25,00	16,80	2,0	
Rotary harrow (5cm deep)	CELLI S.p.A., model 60 200 (2006) Italy	20,83	10,51	2,0	Idem

Compost spreader	Roche père et fils, model R45 (1984) France	12,00	1,95	2,5	
Roller-crimper	Home-made with Atelier Paysan (2014)	9,34	6,18	2,1	
Disc roller	Jean de Bru s.a., model LP22 (1980) France	7,91	6,22	2,3	
Strip tillage (20cm deep)	Home-made with Atelier Paysan (2014)	6,86	2,34	2,5	
Fertilizer spreader	AGRIC, model EP 800 (?) France	3,75	2,25	8,0	

* Consumptions measured on the experimental field by filling the fuel tank before and after each operation

Appendix 6: GRAB's roller-crimper and strip-till

The roller-crimper used was home made with the help of "Atelier Paysan" (Picture below). The roller is 2.21 m wide, weighs 600 kg and has short-staggered straight blades. This year, four blocks of concrete, of 70 kg each, were added because the roller-crimper appeared to be too light to effectively kill the cover crop. The roller weight was then 920 kg. The cover crops were rolled at a speed between 13 and 18 km h^{-1}.



Roller-crimper used for GRAB experiments (GRAB; Atelier Paysan, n.d.)

The strip till equipment was also self-built and was connected to the roller. It is made of a disc to cut the mulch layer and a harrow tine to till the soil on the transplantation line. A fertilizer spreader was combined to the strip till to lay fertilizer pellets directly into the strip tilled (Picture below).

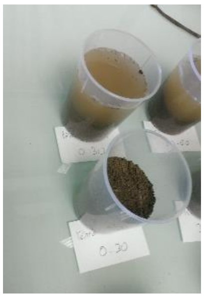
Strip-till combined with the roller-crimper

Appendix 7: Soil nitrate measurement

Nitrate (NO_3^-) soil concentration was measured on two soil layers, 0-30cm and 30-60cm, on all experimental plots.

Soil was collected with an auger (Picture on the right). For each plot, 5 samples were taken out randomly. Soil was crumbled and mixed in a bucket and stored in a cool box.

Then soil was sieved with a sieve with apertures of 5mm in order to break clods and withdraw the stones.



100g of soil was blend with 100g of mineralized water in a plastic pot. It was shaken during 3 minutes and then filtered.

A Merckoquant test strip (Wetselaar et al., 1998) was dipped into the filtrate during 2 seconds. After one minute, nitrate concentration was read on the Nitracheck ® reflectometer (Nitracheck 404, STEP Systems GmbH, Germany). At least two measurements were done.

The strips indicate also the presence of nitrite (NO_2^-), if the above test area colours into pink.

The strips measure NO_3^- concentration in ppm or Mg L^{-1} in the soil filtrate. The formula used to convert it into N- NO_3^- is:

$N\text{-}NO_3^-$ (kg ha^{-1}) = C x NO_3^- (Mg L^{-1})x tf

where $C = \frac{100+H}{100-H}$ x Da x p x $\frac{14}{62}$ x 10

with H = % soil moisture, Da = soil bulk density of sampling ($t.m^{-3}$), p = layer thickness (m), tf = % of fine soil

A constant value of Da = 1.4 was taken (mean value for clay loam soils). Soil humidity was assessed for each sample, weighing a volume of soil before and after 48h of proofer at 105°C.

Appendix 8: Petiole sap nitrate sampling

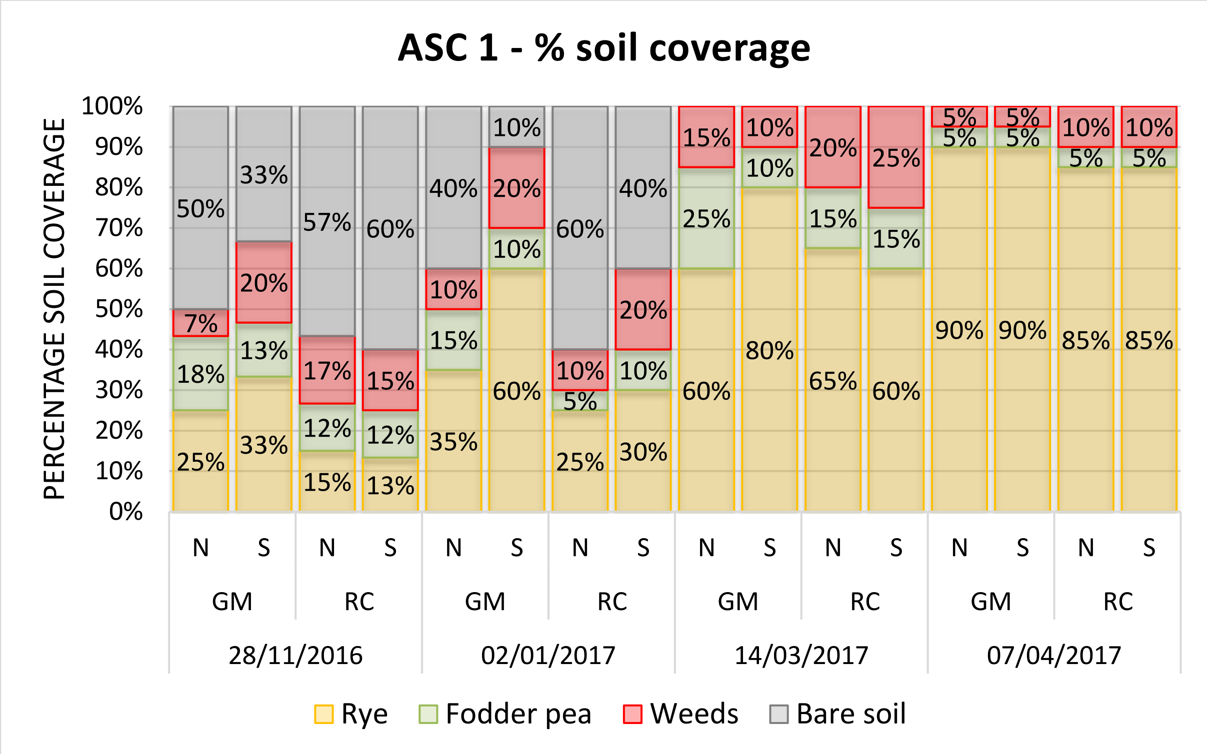
This methodology is inspired from Ctifl PILazo protocol which aim to assess main vegetable species nutrition level (see Raynal Lacroix and Abarza, 2002).

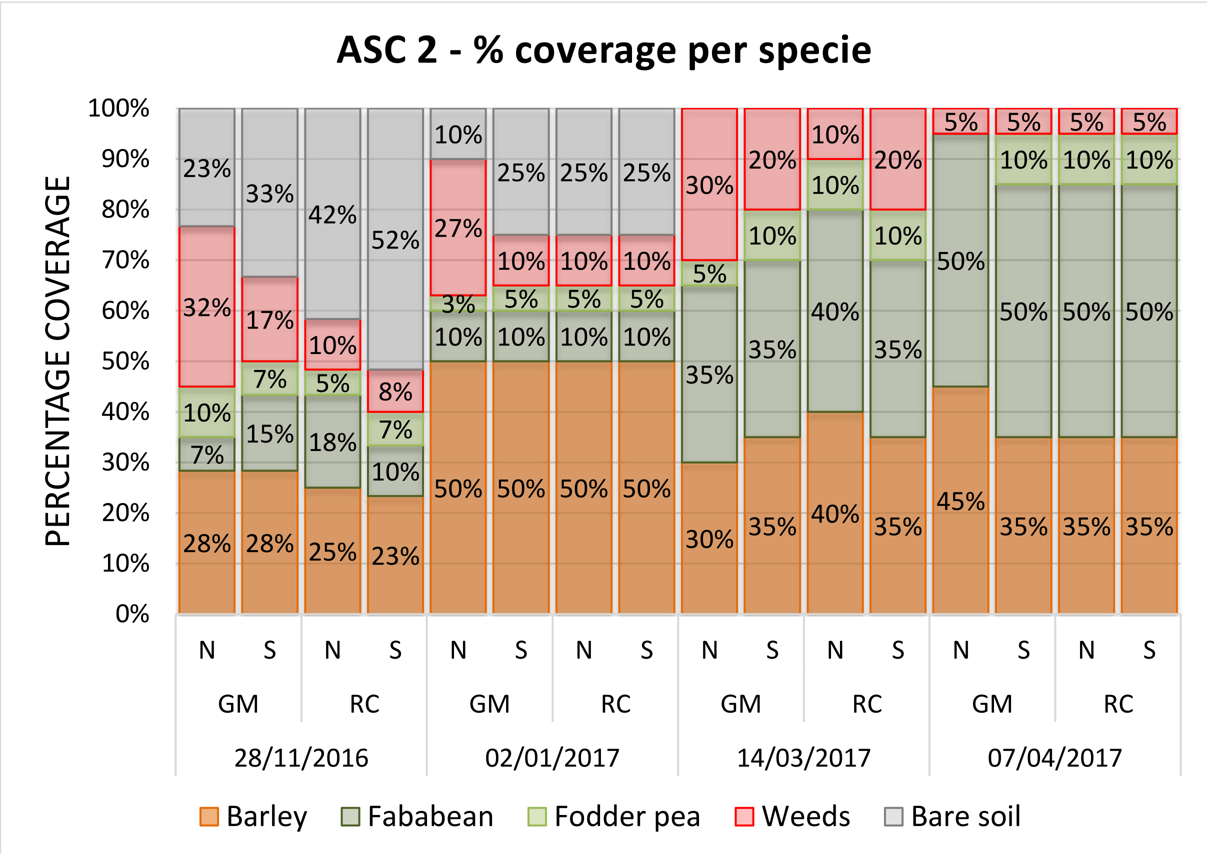
For each experimental plot, 12 young petioles of squash are harvested in the morning (between 8a.m. and 10a.m.), and kept in plastic bags in a cool box until measurements at the laboratory.

The petioles are cut in small pieces with scissors and then crushed with a special squeezer (Challenge Agriculture SARL) to extract the petiole's juice (Picture on the right).

One ml of juice is then taken and is diluted to 1/10th with distilled water. After shaking, nitrate content is measured with Merckoquant test strips and the Nitracheck ® reflectometer (Picture below), as detailed in the Appendix 7.

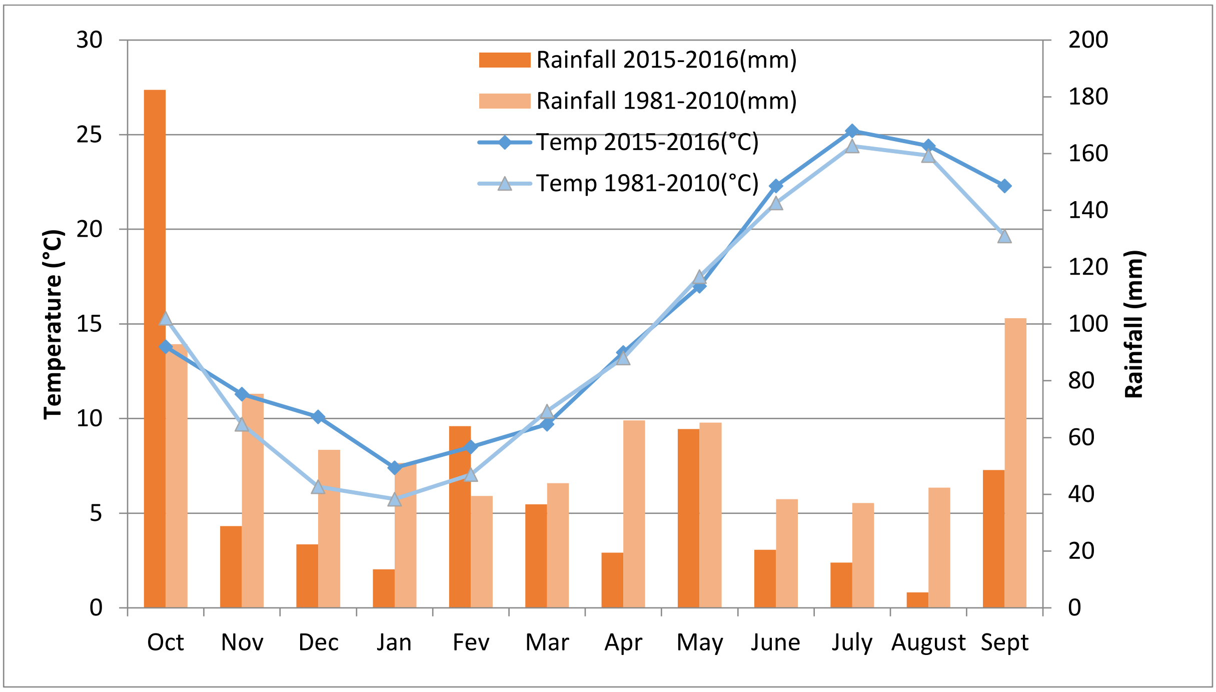
Appendix 9: Percentage ASC soil coverage



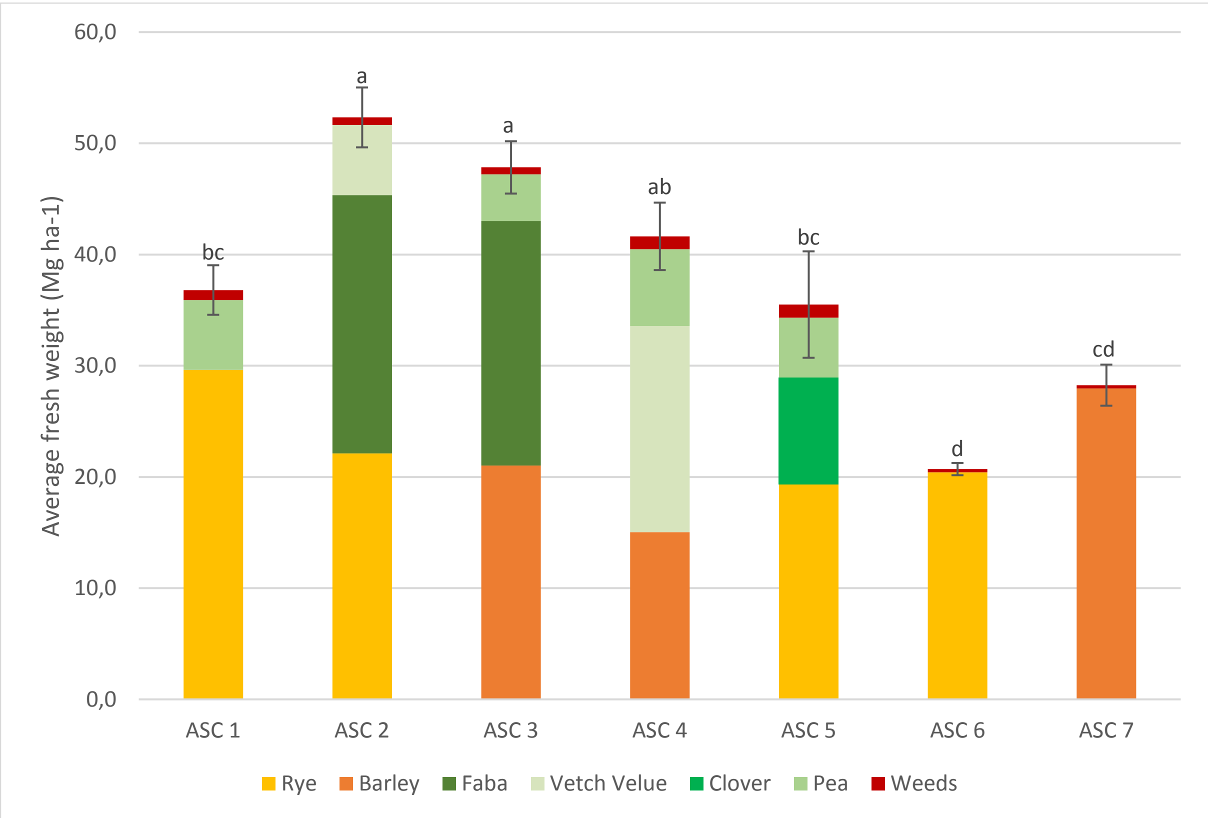


Appendix 10: Results from the experiment in 2015-2016 (Mohrmann, 2016)

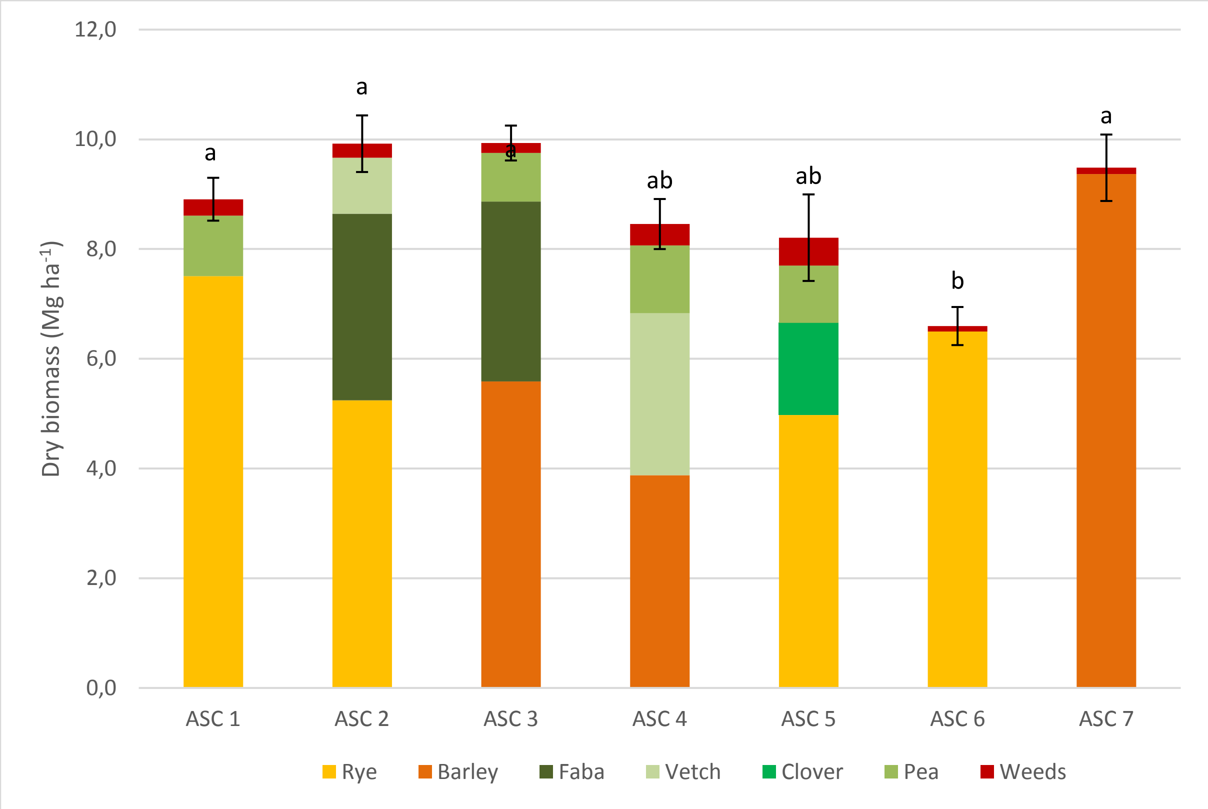
- **Weather**



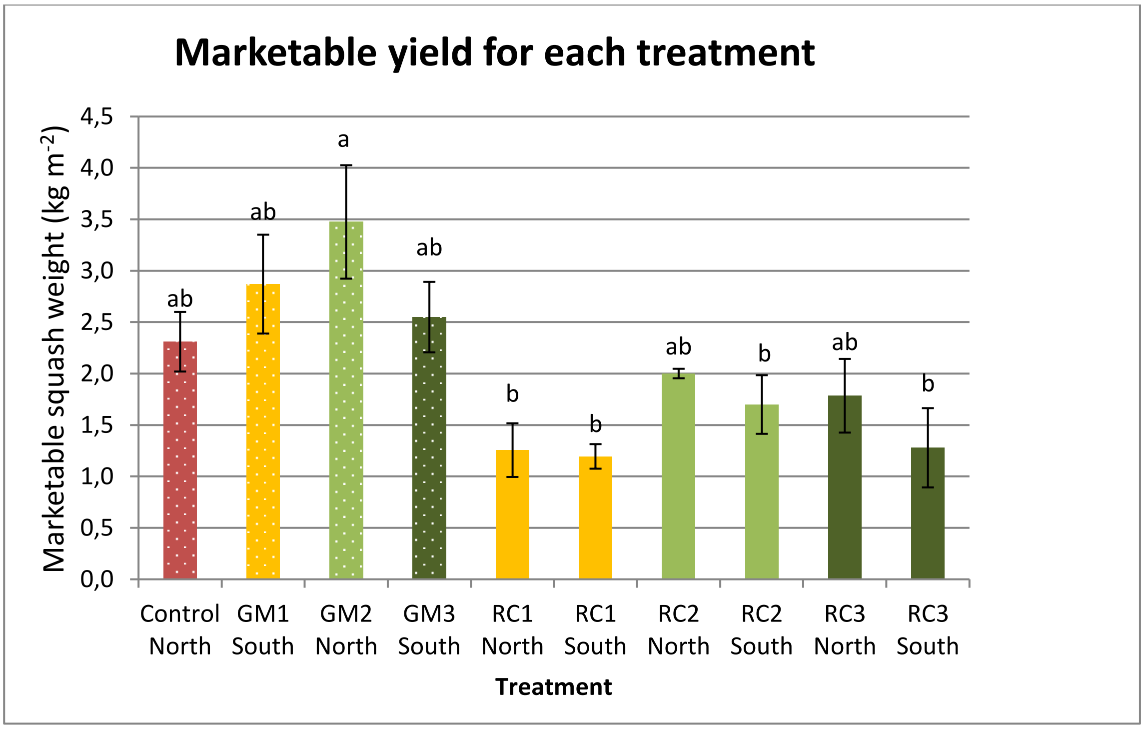
- **ASC fresh biomass production**



- **ASC dry biomass production**



- **Marketable squash yield**



Appendix 11: Roller-crimper references

- **Weight and length of existing roller-crimper (RC)**

Type of RC	**Length (m)**	**Weight (kg)**	**Weight per m (kg m^{-1})**	**Source**
GRAB roller-crimper				
Short-staggered straight blades	2.210	600 (920)*	271.49 (416.29)*	GRAB
Homemade roller-crimper				
Spiral Blades	3.20	832.3 (1195.2)*	260.1 (373.5)*	http://www.farmingwithhorses.com/crop-roller-models-and-prices http://www.newfarm.org/columns/jeff_moyer/ask/2006/1206/1214_3print.shtml (problem of cover crop destruction when the water was subtracted)
Strait blades	2	380 (550)*	190 (275)*	http://www.merfield.com/research/2009/trials-of-a-c rimper-roller-for-killing-cover-crops-for-organic-and-non-herbicide-no-till-cropping.pdf (Rodale Institute)
Flex roller with blades	1.40	300	214	Serfersol
Commercial roller-crimper				
Short-staggered straight blades	6.1	4400	721.3	http://ritewaymfg.com/images/brochures/CrushRite_14_04_web.pdf
Short-staggered straight blades	3.7	1670	451.4	http://ritewaymfg.com/images/brochures/CrushRite_14_04_web.pdf
Spiral Blades	3.2	1520	475	(Mirsky et al., 2009)
Spiral blades	2 - 6		400 (++)*	http://www.gregoireagri.com/Travail-du-sol-Semis-Rouleau-destructeur-de-couverts-vegetaux
Short-staggered straight blades	2.75	1020	370	http://sky-agriculture.com/?-Rouleau-FACA,52-

*Roller-crimper weight with additional weights or filled with water

- **Speed of roller-crimper**

Rolling speed	**Source**
3.2 km/h; 6.4 km/h	(Kornecki et al., 2009)
4.8 km/h	(Kornecki, 2016)
4.68 km/h	(Raper et al., 2004)
> 8.047 km/h	(Smith et al., 2011)
10 km/h; 7km/h	(Atelier Paysan, 2016)