

# PROJECT FINAL REPORT

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**Name of the scientific representative of the project's co-ordinator, Dr. Maria R. Finckh**

**Title and Organisation: Professor**

**Tel: 0049-5542-98 15 62**

**Fax: 0049-5542-98 15 63**

**E-mail: mfinckh@uni-kassel.de**

**Project website address: <http://web3.wzw.tum.de/oscar/index.php?id=2>**



# Optimising Subsidiary Crop Applications in Rotations

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## List of abbreviations

AMF	Arbuscular mycorrhizal fungus
Aryl	Arylsulphatase activity
CC	Cover crop
Chit	Chitinase activity
Cmic	Microbial biomass carbon
CT	Conventional tillage
DFA	Discriminant function analysis
Extr-C	Extractable Carbon
Extr-N	Extractable Nitrogen
H'	Shannon's Index
LM	Living mulch
MUF	4-methylumbelliferone
Nmic	Microbial biomass nitrogen
Ntot	Total nitrogen
Pho	Acid phosphatase activity
RT	Reduced tillage
SC	Subsidiary crop
SEIc	Synthetic Enzymatic Index involved in carbon cycle

## Executive summary

The overall objective of the project OSCAR was to be of use for, and improve sustainability in low-input, organic, and conventional farming systems. The research built on centrally planned multi-environment and long-term experiments on of living mulch (LM) and cover crop (CC) based reduced tillage systems and detailed research on system management optimization, technology improvement, soil ecological services, and dissemination.

LMs can benefit both organic and extensive conventional farming in Europe. For successful LM based cropping high crop densities are needed and regular sowing patterns were best suited. If expected cereal yields  $\leq 6 \text{ t ha}^{-1}$ , a clover LM canopy sufficiently strong to generate a dense sward after main crop harvest can establish in temperate and north Mediterranean environments with mild winters and no water limitation of wheat productivity. In cooler places sowing the LM before the main crop or undersowing in spring can be solutions. High biomass producing CCs can compensate typical negative initial effects of reduced tillage (RT) with respect to yield and weeds. Especially further north, where the growing season is shorter, it is necessary to develop new methods for weed control in spring and autumn. Mechanical tools for subsidiary crop suppression, such as the roller-crimper, work best during flowering of the CCs. Over the long-term RT either was neutral or led to positive effects on yields and weeds especially in the sub-tropical climates in southern Brazil. Increased aggregate stability, higher soil C contents, higher microbial activity, and increase of arbuscular mycorrhizal fungi (AMF) survival were apparent after only one year of RT compared to conventional tillage (CT). AMF contribution to soil P uptake was greater in RT than CT and amounted to up to 30%. Appropriate CCs can sustain AMF during fallow periods and for improved colonization of subsequent crops. Nitrate leaching only played a role under north Mediterranean conditions or when in addition to SCs nitrogen fertilizer was also applied. RT, LM, and CC based systems either resulted in improvements or no changes in subsequent plant health also if the LM were leguminous plants. Potato late blight was significantly reduced in Germany and Brazil in RT combined with dead mulch. Laboratory and greenhouse trials confirmed the potential of volatile and water soluble compounds from *R. sativus* roots to reduce hyphal growth of both *Fusarium graminearum* and *F. culmorum* and the potential of compost to suppress foot and root rot diseases of peas, depending on compost type, age, and pathosystem. The modular structure of the WEco-Dyn machines allows a wide range of applications, from clean soil tillage to prepare a seedbed up to minimum and no-tillage systems combined with direct sowing but in-depth technological support and training for farmers willing to change to RT is needed. Rhizome-root fragmentation is a less intensive control method for perennial weeds compared to soil tillage and should be combined strategically with other preventive measures. New legume and non-leguminous CC species of interest were identified for selection and breeding. Resistant accessions of different species in several genera were identified in the OSCAR project and represent valuable genetic material for future breeding programs for small grain legumes. Economic modeling resulted in a wide range of potential outcomes of RT and SC based cropping systems in the short term and clear advantages in the long term. The methodology used will be able to integrate the long-term effects of soil fertility as factors of sustainability of reduced tillage and subsidiary cropping systems.

Subsidiary crop application is essential for no-tillage systems to be sustainable. and is possible under a wide range of conditions, for LM as well as for CCs. RT combined with enhanced use of subsidiary crops and appropriate field technology has a high potential for improving efficiency of the cropping system, reducing resource use and increasing overall sustainability. Making the knowledge available to the public with the Cover Crop and Living Mulch Toolbox was a major step in supporting farmers in choosing species of LM or CC appropriate to their regions and systems and for encouraging others to contribute more to this important collective effort.

## Summary description of project context and objectives (4 pages)

### Introduction

There is widespread concern over the damage caused by modern agriculture to soil structure and the ecosystem services provided. One approach to overcome this problem is conservation agriculture (CA) which aims to maintain soil structure by minimizing soil disturbance, maximizing soil cover and using crop rotation. However, despite recent legislation supporting minimum tillage and direct seeding, together with the efforts of pioneer farmers, CA is still practiced on less than 4% of the agricultural land in Europe (SoCo Project Team, 2009), while, for example, in Brazil the share of CA is more than 60% (Mello and van Raij, 2006). The slow progress in Europe underlines the need for major improvements in the approach together with consolidation of, and access to, information about alternative cropping methods and their biological and economic value and performance.

Most current reduced soil tillage systems are based on highly simplified rotations accompanied by large increases in agrochemical inputs, especially herbicides and fertilizers, as well as pesticides that pose problems to soil quality and biodiversity. A recent meta-analysis of the productivity limits and potentials of CA clearly showed that without the use of cover crops and rotations, minimum tillage will in most cases lead to long term yield decline (Pittelkow et al., 2015). The majority of agricultural soils are suffering structural deficiencies and other damage due to overuse of inputs, intensive tillage operations, lack of diverse plant communities and soil cover, a simplified soil food web and widespread presence of soilborne diseases. Little is known about how specific improved management approaches are affected by pedo-climatic conditions (Scopel et al., 2013) and many of the intricate interactions affecting soil nutrient dynamics and soil quality are not well understood. To a certain degree, successful soil management systems are individual cases and will always be site-specific but should be guided by scientific principles applicable to different pedo-climatic and agroecological conditions. The net effect of encouraging crop diversity within rotations should fit well with the current ecological view of positive correlations between diversity and stability, on the one hand, and between diversity and productivity on the other (Moreau, 2010; Palm et al., 2014).

To extend soil cover, CA uses subsidiary crops (SC) grown either as cover crops (CC) preceding or following the main crops, or as living mulches (LM) together with the main crops. There is an urgent need to review the current SC and to determine the value of other crops for use in such systems, particularly to cover the range of environmental variation across Europe. Appropriate choice and timing of use of such crops, adapted to regions, can help to minimize tillage and to reduce weed problems. Complementary development of appropriate tillage technology can also help to reduce the direct effects of soil disturbance while encouraging establishment and development of both SC and main crops.

OSCAR aimed at developing improved ways of integrating subsidiary crops (SC) as living or dead mulches or cover crops with the main crops in rotations so as to simultaneously improve crop nutrition, health, and productivity. The SC will deliver multiple ecological services by increasing the duration of soil cover in the rotation overall while increasing species diversity, minimizing the use of tillage and agrochemicals, enhancing biological N fixation and soil C content, and both reducing water demand in dry climates and improving soil workability in wetter climates.

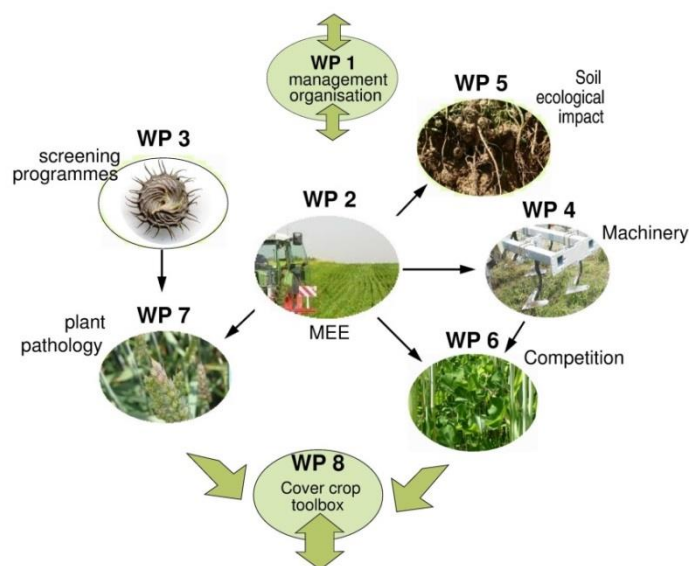
### Project objectives

The overall objective of the project as a whole was to be of use for and improve sustainability in low-input, organic, and conventional farming systems. The research drew on a wide range of

previous and ongoing EU and related projects and on centrally planned multi-environment and long term experiments.

The project was organized in eight work packages (WPs) (Figure 1). Besides management, WP1 had the objectives to increase visibility of the project and increase the impact of the research and to disseminate solutions for CC- and LM-based systems to a large audience of potential new users. WP2 – WP7 were research centered while the central deliverable of OSCAR was a database supported 'Cover Crop and Living Mulch Toolbox' and Decision Support Tool that encourages stakeholder exchange and dissemination during and beyond the lifetime of the project so as to capture farmer experience.

Breeding companies and manufacturers of agricultural equipment were involved in finding adapted solutions for the different environments by extending the range of potentially useful plant species and by developing appropriate machinery to promote adoption in practical agriculture. The potential for useful chemical extraction from the existing and novel SCs was also investigated.



**Figure 1. The eight work packages (WPs) of the OSCAR project and their relationship to each other.**

**WP2: The Multi-Environment-Experiment (MEE):** Different cover crop (CC) and mulch systems were compared in the context of a series of coordinated field trials in different European and Mediterranean environments in a multi-environment experiment (MEE). A two-year sequence of wheat and a spring crop (maize, potatoes, or vegetables) was the common experimental base for the MEE upon which to compare the different cover crop and mulch systems.

In the MEE, only short-term effects of soil management, cropping systems or subsidiary crops could be investigated. Though these are important for phases of conversion to different cropping systems, long-term effects also have to be considered. Therefore, three already running long-term experiments (LTE), examining similar soil management and cropping systems, were included in the analysis to assess the long-term effects of subsidiary crop based minimum-tillage systems.

The MEE and LTE experiments were assessed for economic and ecological impact including the often neglected issue of legume root health. Specific objectives of WP2 were (i) to provide the common experimental framework for part of WP 4 (Machinery), WP 5 (Assessment of soil ecological impact), WP 6 (Competition), and WP 7 (Phytopathology); (ii) to serve as a demonstration and for dissemination purposes in WP 1; (iii) to evaluate the short term and long-



term effects of SC based minimum tillage systems economically, and (iv) to generate information for the cover crop Toolbox in WP 8.

**WP3: Identification of new species and genotypes and additional uses:** The overall objective of this WP was to increase the range of SC species and make more adapted species/varieties available to fill niches in crop rotations. Cover crops (CCs) should be fast growing and highly productive and fit in the off-season between main crops. In contrast, living mulch (LM) should not be too competitive and it should be complementary with the main crop, i.e. occupying the niches not used by the main crop. Both types of crops should contribute to soil fertility and/or soil health as much as possible and potentially generate additional income. While perennial and self-reseeding forage legumes are of high interest due to their N-fixing ability, non-leguminous species may have beneficial effects on soil health and quality and general biological diversification. For many CCs species mixtures (e.g. legumes and grasses) are the rule rather than the exception, adding to biodiversity and system stability. When no cash crop is to be produced, both LM and CC should be designed as much as possible as species mixtures to enhance biological diversity.

The objectives of WP3 were (i) to identify new species of interest as LM or CC, both legumes and non-legumes as single species and mixed species stands; (ii) to identify genotypes of currently used perennial *Trifolium repens*, *T. subterraneum* and other legume species better adapted for use as LM including possibilities of improved seed production systems; (iii) to identify genotypes of annual self-reseeding species adapted for use as LM and to cold winters; (iv) to assess potential alternative uses of new species – e.g. value as livestock feed or for industrial processing; and (v) to establish how quickly and accurately knowledge on the suitability of CC/LM species can be obtained by farmers directly on their farm.

**WP4 Farm technology and machinery:** In order to reduce the dependence on herbicides and to reap maximum benefit from SCs in practice the availability of the appropriate technology for sowing and termination of the SCs is crucial. WP4 was to develop and make available technical solutions. The specific objectives of the WP were (i) to identify needs and available solutions; (ii) to design and implement an experimental modular system to test different technical solutions for cover crop application; (iii) to design and test sowing implements for CC suppression, seeding and transplanting arable crops and vegetables, meeting the particular requirements of CC based cropping systems; and (iv) to test and improve machinery for more effective weed control and soil fertility management.

**WP5 Soil ecological impact:** One of the main aims of LM and CC based agricultural systems is soil protection and improvement of overall soil fertility and sustainability by increasing ecological services. Therefore, the objectives of WP5 were (i) to assess soil fertility parameters such as soil organic matter and microbial activity including mycorrhiza populations and nutrient (especially N) supply; (ii) to determine system effects on C sequestration and (iii) to determine system effects on nitrate leaching and erosion. Indicators for N and C dynamics as well as for microbial activity and diversity across a wide range of environments were assessed. Soil biochemical activity and microbial respiration as important indicators of the nutrient biogeochemical cycle for soil fertility assessment as well as effects of CC and LM on mycorrhizal abundance were assessed. In addition, the potential impact of the various SC applications on erosion risk at different sites was also assessed in the project, based on ground cover data, aggregate stability and climatic and topographic data.

**WP6 Methods for regulating competition and perennial weed control:** Managing the interactions among component species is a major challenge in developing sustainable multi-species production systems. Farmers have many agronomic options available, but our limited understanding of the mechanisms governing these interactions among species in the field means that we do not have reliable basic principles to apply in constructing multi-species production

systems out of the myriad of possibilities that exist. The overall objective of WP6 was to fill key knowledge gaps on the agronomy of SC and LM based cropping systems with emphasis on managing competitive interactions. Specifically, objectives were (i) to describe and evaluate the most important management factors affecting competition among main crop, LM, and weeds and to identify the most efficient tools for regulating competition; (ii) to analyze the parameters of competition in the MEE; and (iii) to identify the most critical weeds in CC and LM based cropping systems and to develop and evaluate innovative methods of weed control in no-tillage or minimum-tillage systems.

**WP7 Phytopathological risks and solutions:** The potential agronomic and environmental benefits of leguminous and non-leguminous CC/LM and reduced tillage can only become effective if their pathological risks for a rotation are thoroughly assessed and solutions to potential problems are identified. While it is expected that air-borne diseases will be reduced through LM due to physical inhibition, especially non-specialized soil-borne pathogens may increase if they can survive on residues and alternate hosts. However, they may be reduced through the use of CCs and species mixtures using LM with reduced tillage if higher organic matter leading to enhanced microbial and faunal activity increase crop residue breakdown and overall increase disease suppressiveness (van Bruggen and Semenov, 2015). Legumes are most critically affected by soil-borne pathogens (Finckh et al., 2015) as these not only reduce productivity but also N-fixation. Also, several important legume foot and root pathogens are rather generalist among the legumes and sometimes even attack additional hosts, such as main crop cereals with potential negative impacts with respect to mycotoxin contamination on cereals. Host specificity and ways to increase soil suppressiveness are therefore key traits to be studied.

WP7 aimed at (i) studying the disease dynamics (air- and soil-borne) in CC and LM systems with different tillage strategies established in the MEE and LTE experiments under different climatic conditions; (ii) studying the effects of LM and CCs and improved soil management on system health, i.e. survival of major soil-borne pathogens and epidemiology, dispersal and mycotoxin production of *Fusarium* fungi in the following main cereal crops under field conditions; and (iii) to screen LM and CC species identified in WP3 for their susceptibility to soil-borne pathogens.

**WP8 Cover Crop and Living Mulch Toolbox:** Greatest impact efficiency will be ensured by drawing together (a) new knowledge gained from within the project as a whole, and (b) pre-existing knowledge bases. Accessing relevant information is time-consuming, inefficient and potentially imprecise. For example, agricultural engineering innovations relevant for SC are only available in relatively limited geographical areas, despite larger potential. Similarly, innovations involving novel SC species or new germplasm are rarely communicated over the entire potential eco-climatic region. The overall objective of WP8 was to facilitate improvement of CA and SC systems throughout Europe by making relevant high-quality information available to target groups. Specific objectives of WP8 were (i) to make scientific and technical information on CC / LMs based systems widely available to all stakeholder communities; (ii) to promote the impact and awareness of innovative SC systems and the associated solutions to ecological problems; and (iii) to allow direct participation by the stakeholder community through an interactive database and decision support tool.

Limitations to the adoption of LM and CC based cropping due to language barriers and other availability issues are reduced by the Toolbox bringing information together to a central source and translating relevant information. As the main impact delivery tool of the project, this central WP ensures that contributions of the research are focused on adaptability, solutions and innovative change.

## Main Results (not exceeding 25 pages)

### WP2: The Multi-Environment-Experiment (MEE) and Long-term Experiments (LTEs)

#### Experimental factors and design

The MEEs were set up to compare effects of conventional tillage (ploughing) and minimum-tillage or no-till in the second year of a rotation of wheat combined with various subsidiary crops (SC) followed by a spring sown test crop (Figure 2). The different methods of using SCs were:

1. No SC (“control” treatment = conventional cropping system); main crop and test crop only;
2. The SC is planted at the end of the main crop cycle as cover crop (CC) and then killed before or at the same time as planting the test crop (SC based cropping system 1);
3. The SC is planted at about the same time as the main crop as a living mulch (LM) to be killed before or at the same time as planting the test crop (SC based cropping system 2).

Year (month)	Year 1						Year 2					
	2	4	6	8	10	12	2	4	6	8	10	12
Conventional cropping system	Wheat						Maize/Vegetables (ploughed)					
							Maize/Vegetables (NT)					
SC based CS (1) (Living mulch)	Wheat						Maize/Vegetables (ploughed)					
	Subsidiary crop						Maize/Vegetables (NT)					
SC based CS (2) (Cover crops)	Wheat						Maize/Vegetables (ploughed)					
	Subsidiary crop						Maize/Vegetables (NT)					

**Figure 2. Structure of the MEE trials.**

All partners chose a split-plot design, mostly with the soil tillage system, in some case also with the subsidiary crop as main factor. The main crop in the first year was bread wheat, the main crop in the second year in most cases maize, in some cases, tomatoes, potatoes or barley. The experiments were performed in 12 different environments (Table 1). Experiments were harmonized where possible with respect to seeding densities, inter-row distances and the subsidiary crops. Wheat seeding rates were usually 400 grains/m<sup>2</sup> with row distances of 12.5-13.5 cm. Exceptions were the trials of INRA and ICARDA, because larger row distances are generally used in dry climates and KU where 30 cm row distance is used to enable hoeing and/or interplanting in organic crops and LM were sown in between wheat rows. Otherwise two rows of wheat were alternated with one LM row.

The living mulch was sown together with the wheat except in Scandinavia and Poland, where it was undersown in spring. Where possible, subterranean clover (*Trifolium subterraneum*) “Campeda” was used in the MEEs (Table 1). In the Northern areas white clover (*T. repens*) and/or white clover-grass-mixtures were used and at ORC, yellow trefoil was used. The legume cover crop was in most cases Vetch (*V. villosa*) with the exception of the two sites in Morocco (Berseem clover (*T. alexandrinum*)). Several brassica species, such as oilseed radish, mustard, or rape and mixtures of black oats with brassica sp. were used as non-leguminous CCs (Table 1).

In the second year of each cycle, the main crop was planted using implements newly developed in WP 4. This comprised a seeder equipped with shallowly undercutting tools in order to suppress weeds and subsidiary crops and thus allowing for avoiding or reducing the use of herbicides. For transplanting tomatoes at UNITUS in Italy, a transplanter capable of transplanting in mulch layers has been developed. In the experiment of KU, where potatoes were grown in the second year, soil preparation was done by grubbing 12 cm deep in the minimum-tillage treatment in contrast to the plough. In addition, after the first hilling operation, the potatoes in the minimum tillage treatment

were mulched with fresh green materials and no more hilling was performed. (Figure 3). In organically managed experiments, weed control was achieved by shallow undercutting; in two conventionally managed environments (TUM and ART) this was compared with conventional direct drilling, using herbicides for weed control.

**Table 1. Climate zones, partners, cropping systems, and experimental factors included in the Multi-Environment and Long-Term (LTE) experiments.**

Climate zone <sup>1</sup>	Partner, country, system <sup>2</sup>	Main crops		Subsidiary crops		Experimental factors
		1st year	2nd year	LM <sup>3</sup>	CC	
NEM	SLU (SE), conv. Swedish University of Agricultural Sciences	Soft Wheat	Maize	W. clover; W. clover + ryegrass	Oil radish, vetch	2 N levels
BOR	BIOFORSK (NO), conv. Norwegian Institute for Agricultural and Environmental Research	Soft Wheat	Barley	W. clover; W. clover + ryegrass	Vetch Brassica	2 N levels
ATC	ORC (UK), org. The Organic Research Center	Soft Wheat	Barley	Yellow trefoil	Brassica spp. Vetch	
CON	ART (CH), conv. Agroscope Reckenholz-Tänikon,	Soft Wheat	Maize	S. clover	Vetch Oil radish	2 N levels, herbicides
CON	TUM (DE), org. Technical University of Munich	Soft Wheat	Maize	S. clover W. clover	Mustard Vetch	
	TUM (DE), conv.	Soft Wheat	Maize	S. clover	Mustard Vetch	2 N levels, herbicides
ATN	KU (DE), org. University of Kassel,	Soft Wheat	Potatoes	S. clover; W. clover	Brassica spp., Vetch	+/- compost
CON	IUNG (PL), conv. Institute of Soil Science and Plant Cultivation	Soft Wheat	Maize	W. clover ryegrass	vetch	2 N levels
MDN	UNITUS (IT), conv. Università degli Studi della Tuscia	Durum Wheat	Tomato	S. clover	vetch Brassica	2 N levels
	UNITUS (LTE, 2001) org. / conv.	Chickpea-Durum Wheat, Tomato		-	Vetch, oil seed rape	3 N levels
MDN	UNIPI-SSSA (IT), (LTE, 1993) conv. University of Pisa / Scuola superiore Sant'Anna Pisa	Sunflower, Durum Wheat, Maize, Durum Wheat		S. clover	Rye, crimson clover	4 N-levels, low-input
MDS	INRA (MO), conv. Institut National de la recherche agronomique	Durum Wheat	Maize	S. clover	Berseem clover	2 N levels, low-input
MDS	ICARDA (MO), conv. International Research Center for Agricultural research in Dry Areas,	Durum Wheat	Maize	S. clover	Berseem clover	2 N levels, low-input
Subhumid tropical	IAPAR (BR), (LTE, 1986), conv. Instituto Agronômico do Paraná	Maize and Soybean		-	12 cover crops <sup>4</sup>	2 N levels

<sup>1</sup>Climate zones according to (Jongman et al., 2006): NEM-Nemoral, BOR-Boreal, ATN-Atlantic North, ATC-Atlantic Central, CON-Continental, MDN-Mediterranean North, MDS-Mediterranean South.

<sup>2</sup>Partner abbreviations as used in the text and country codes in parentheses. Conv.-conventional cropping system; Org.-organic cropping system; LTE, year: long term experiments of these partners started in the year noted were evaluated.

<sup>3</sup>W.clover, S.clover: white and subterranean clover

<sup>4</sup>CCs used in Brazil: White lupin + black oat IAPAR-61, hairy vetch, common vetch, wheat, ryegrass, Hairy vetch + Black oat IAPAR-61, rye, radish-IPR-116, white oat (IPR-126), blue lupin, fallow, black fallow.

The long-term experiments (LTEs) are located in Italy (UNIPI/SSSA, UNITUS) and Brazil (IAPAR) (Table 1). The long term crop rotation experiment of IAPAR with maize and soybeans and 12 CC options combined with tillage and N applications was established in 1986 at the Experimental Station at Pato Branco, southern Parana State and has been described in detail (Calegari et al., 2008). At UNIPI, since 1993 the main crops are rotated according to a 4-year crop sequence managed under rain fed conditions (Table 1) with two tillage systems, four N fertilization rates, and four soil cover types in a split-split-plot design with four replications. The LTE of UNITUS was



established in 2001 to compare innovative organic vs. conventional cropping systems and plowed vs. subsoiled soil. A 3-year crop rotation was established with two cover crops (Table 1).



**Figure 3. Top row: Maize seeding with WEco-Dyn (left), undercutting (center), hairy vetch after mowing at flowering stage (at right; MEE, TUM, 2014). Bottom left and center: Ferrari transplanter at work and tomato plants transplanted into cover crop mulches at UNITUS experimental farm. Bottom right: Application of fresh mulch of triticale and vetch to minimum till potatoes at KU.**

### Assessments

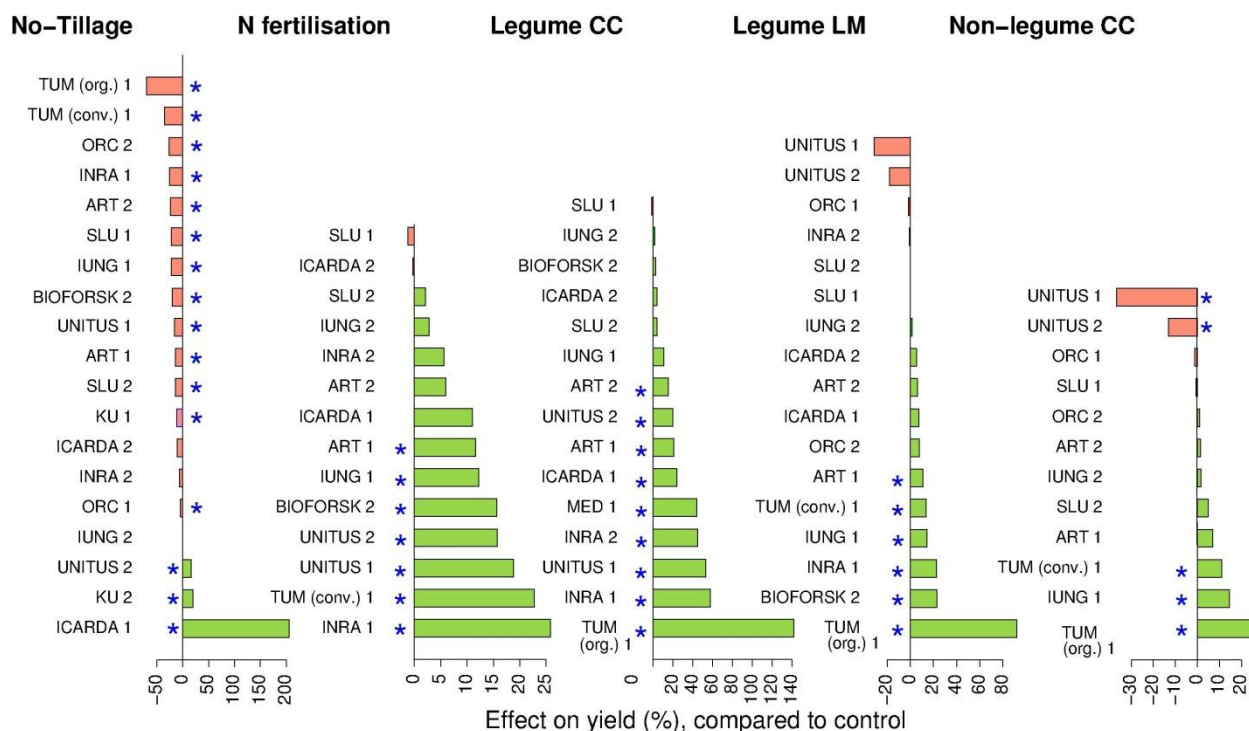
Among others, Crop density, ground coverage by the main crops, cover crops and weeds (in different growth stages), canopy height, biomass of the main crop, subsidiary crop and weeds, crop yields, diseases and stress symptoms were evaluated. Additional assessments on soil ecological services, weeds, and diseases were performed in selected MEEs and LTEs as described in WP5, 6, and 7 below, respectively.

### Wheat performance

Wheat yield levels ranged from approx. 2.5 t ha<sup>-1</sup> in Mediterranean sites to 8 t ha<sup>-1</sup> in Northern Europe. The effect of N fertilization was as expected, except for the areas where grain production is limited by water availability. True living mulch, i.e. a clover canopy growing together with wheat from the beginning was established at KU, TUM (organic and conventional), ART, UNITUS, INRA and ICARDA. At KU and the two Moroccan sites, subterranean clover did not establish and develop well. At TUM, the effect of the subterranean clover living mulch was only slight, despite a considerable canopy of subterranean clover under that of wheat. In the Mediterranean environments (UNITUS, UNIP), competition for water was higher leading to slight negative effects. Lower yields with subterranean clover living mulches, however, might also be due to the wider row distance and consequently lower seeding density of wheat. The LMs that were undersown in spring (IUNG, ORC, SLU, BIOFORSK) had hardly any effect on wheat yield (data not shown).

### Second crop performance

Maize yields varied greatly at the different locations in the MEEs, ranging from 3.5 to more than 9 t ha<sup>-1</sup>, depending on the management system (conventional vs. organic). Effects of tillage, N fertilization level and SCs were often statistically significant (Figure 4).

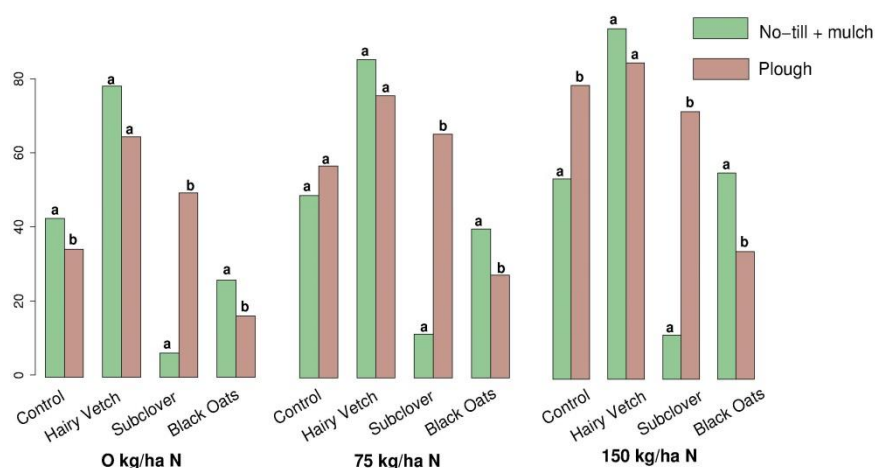


**Figure 4. Effect of subsidiary crops, soil management and N fertilization on Second crop yield in the MEEs in 2014 (marked with 1) and 2015 (2), expressed in percent of the control treatment (ploughing, low N fertilization level, no subsidiary crop, respectively). \*=significant deviation from the control (t-test,  $p < 0,05$ ). Second crop was maize except for: BIOFORSK and ORC (Barley), UNITUTS (Tomatoes), KU (Potatoes) (See Table 1 for details).**

Overall, in the short term second crop yields tended to be 10 to 20 % lower in the no- or minimum-tillage plots in most environments. At TUM, the seeding/undercutting device did not perform well on the relatively heavy soil; weed control, maize germination, establishment and the overall crop density was consequently irregular and relatively low. In the organically managed site of TUM, the establishment of Maize in the minimum-till system failed almost completely with most subsidiary crops due to reduced N availability, competition by surviving subterranean and white clover as well as high weed pressure. Only with vetch as CC weed pressure was sufficiently low and N availability sufficiently high to allow for the development of a productive maize canopy. Similar tendencies could be observed for Barley, which was cultivated at ORC and BIOFORSK under organic management. At ICARDA, where water was limiting no-tillage helped avoid water losses and maize yields were higher than in the tilled version. Also, in the Experiment of KU in the second year with potatoes as main crop, the better performance in the reduced tillage treatments may be explained by better protection from evaporation in the mulched plots in the very dry second year.

The SC species had the most remarkable effect on second crop yields and this was related to their biomass that was highest in vetch and subterranean clover resulting in weed suppression and higher N supply. In the case of vetch this was so high, that additional N fertilization did not (or hardly) enhance yield in a part of the environments. Especially in organically managed environments, non-legume CCs often did not develop well due to low N availability after wheat. Positive effects of the non-legume CCs in the organic trials at TUM were mostly due to the soil movement effects at sowing that reduced weeds and may have stimulated mineralization.

In contrast to the negative effects of RT observed for maize and barley in the MEEs, the highest tomato yields at UNITUS were always obtained with vetch as CC and RT independent of fertilizer input (Figure 5). Biomass of vetch was considerable resulting in a highly effective mulch layer (see Figure 3 bottom left) better suppressing weeds than the combination of ploughing and herbicides.



**Figure 5. Tomato yields MEE at UNITUS in 2014 as affected by tillage, N levels and subsidiary crops. Columns within N level and tillage marked with different letters differ significantly at  $P < 0.05$  (LSD).**

In contrast to the short term MEEs, in the LTE in Brazil, maize and soybean grain yields in no-till were significantly higher in the no till system. Maize yielded 7.2 and 7.6 t ha<sup>-1</sup> in no-till and 5.2 and 7.1 t ha<sup>-1</sup> in conventional tillage systems in 2013 and 2015, respectively and in 2014, soybean yielded 1.8 and 1.3 t ha<sup>-1</sup> in no-till and conventional tillage systems, respectively.

### Economic performance

The aim of the economic assessment within the OSCAR consortium was to determine the economic performance of conventional and reduced tillage as well as different subsidiary cropping systems as conducted by the OSCAR experiments in the different partner institutions. The calculations were to be based on the respective crop management of each partner location including machinery use, fertilizer, herbicide and pesticide input as well as overall energy input. Most importantly, the balance between costs and benefits of cropping systems were to include the yield of main crops in competition with or followed by subsidiary crops and the yield of succeeding main crops, which may benefit from the previous subsidiary crop. Changing crop yields as well as differing management measures were assumed to lead to both changes in the economic as well as the environmental efficiency.

The net economic benefit and selected environmental indicators of the OSCAR cropping systems were evaluated with a cost-benefit analysis for the two-year cropping cycles, by carrying out a cost determination of subsidiary cropping systems, by determining an Energy/Yield-Index integrating prioritized and essential energy inputs as well as yield data, and by analyzing the economic risk potential based on the provided yield data using a stochastic risk modelling approach.

The economic results are quite heterogeneous amongst locations, tillage systems and subsidiary cropping systems. Even though there are distinct differences in management and input costs depending on tillage and cropping system, profitability is strongly determined by yield levels. While in many partner locations CT systems attain higher profitability than RT systems, subsidiary cropping (SC) systems are often more profitable than their respective control trials, independent of the tillage system (Table 2).

Reduced tillage usually implies lower management costs. However, in the majority of cases observed within the OSCAR short term trials (two-year crop rotation) the disproportionately lower yields in RT systems lead to a lower profitability than in CT systems. Still, certain RT cropping systems are more profitable than other CT cropping systems. Furthermore, encouraging results from the IAPAR long term trials indicate higher yields with lower management costs for RT cropping systems, leading to greatly improved economics compared to CT systems. Comparing

subsidiary cropping (SC) systems with their respective *control* systems, SC systems display higher or lower economic benefits and energy efficiency, again very much depending on each OSCAR location with their respective energy input, direct and management costs and yields.

**Table 2: Net return after charge for unpaid labor/management and interest charge [€ ha<sup>-1</sup>] for conventional (CT) and reduced (RT) tillage systems as well as for exemplarily selected control and respective subsidiary cropping systems of all OSCAR partner locations**

Partner location	Subsidiary crop/ treatment	Conventional tillage	Reduced tillage
ART	Control N70	1,566	1,025
	Vetch N70	1,633	1,249
TUM (conv.)	Control N140	1,163	692
	Oilseed radish N140	1,186	888
SLU	Control N45	658	661
	Mustard N45	466	503
IUNG	Control	1,901	1,210
	Mustard	1,567	1,291
INRA/ ICARDA	Control N high	229	-87
	Berseem N high	838	380
	Control N low	-63	76
	Berseem N low	-90	21
IAPAR	Control N90	123	1,212
	Blue Lupin N90	-381	1,441
UNITUS	Control N50	3,778	3,668
	Vetch N50	3,792	5,273
UNIPI	Control N2	221	435
	Squarrose clover N2	345	235
TUM (org.)	Control	1,586	1,284
	Subterranean clover	2,190	1,287
KU (org.)	LM White clover	9,470	8,421
	CC Vetch	10,717	9,646
BIOFORSK (org.)	Control N low	487	166
	White clover N low	443	281
ORC (org.)	Control	4,222	3,272
	Brassica	3,993	2,975

Reduced tillage systems usually have a lower energy input than CT systems. Depending on yields, however, this does not automatically lead to higher energy efficiency in RT systems, and no conclusive statement can be deduced on the favorability of one or the other tillage or cropping system from the OSCAR trials.

Risk analysis indicates that integrating subsidiary crops may help to decrease production risks in some locations, for other locations in *control* systems a lower variance of yield results was observed, reducing the risk potential. Disregarding the mean or expectancy value of the economic result for cropping systems, risk distribution can be more favorable for CT than RT systems and vice versa, depending on location.

Consideration of long term effects (nutrient availability, soil fertility) could substantially improve economic feasibility of reduced/no tillage and subsidiary cropping systems. Our analyses also indicate that the monetary effects of considering the value of nitrogen for subsequent crops can have a much higher economic impact than the adaptation of farm size and mechanization to regional agrarian structures.



### WP3: Identification of new species and genotypes and additional uses

In the screening program of OSCAR, about 130 species and more than 1000 legume accessions were tested for their potential as subsidiary crops. Materials originated from collections of ICARDA, TUM, the Center for Legumes in Mediterranean Agriculture, Perth Australia, and the U.S. Department of Agriculture. Most accessions had been collected from wild populations or derive from cultivated ecotypes. A special focus was on subterranean clover and its potential for use as living mulch in Mediterranean and temperate climatic conditions including winter hardiness and persistence trials with more than 300 accessions. All subspecies (*Subterraneum*, *Brachycalycinum*, *Yannicum*) were represented, as well as registered cultivars and ecotypes. Populations collected at altitudes up to 1000 m were comprised, in order to identify genotypes adapted to cold winters.

Since only few seeds of each accession were available in the beginning, the first step was seed propagation, which mostly was done in the greenhouses of TUM. In a second step, unreplicated rows were planted in the experimental stations of TUM and ICARDA depending on species. Selected accessions were successively tested in plots in a broader range of environments. Screenings were performed at two locations in Morocco (ICARDA), Southern and Northern Germany (TUM, PHP), in the UK (ORC), and in the Mediterranean mountains and Mediterranean North (ARCOIRIS, UNITUS). In Morocco and Italy, all experiments were established in fall, while in Germany, all accessions were tested both in spring and as overwintering crop. Seed production, shattering, and mechanical harvestability as well as the occurrence of hard-coated seeds were evaluated in the most promising accessions.

Besides legumes, 25 non-legume species belonging to 20 different genera were tested in order to identify suitable mixture partners in Central Italy (ARCOIRIS) and Southern Germany (TUM). The accessions were planted in rows in the first year. In the following year, the most promising species were planted in replicated plots and in mixtures with subterranean clover and spring vetch.

#### Potentially adapted new species and genotypes

Only a few significant results are reported here. A comprehensive repository of all results can be found in our on-line database ([http://web3.wzw.tum.de/oscar/toolbox/SC\\_DB\\_home.html](http://web3.wzw.tum.de/oscar/toolbox/SC_DB_home.html)) and in the "Cover crop and Living mulch Toolbox" (<http://www.covercrops.eu>).

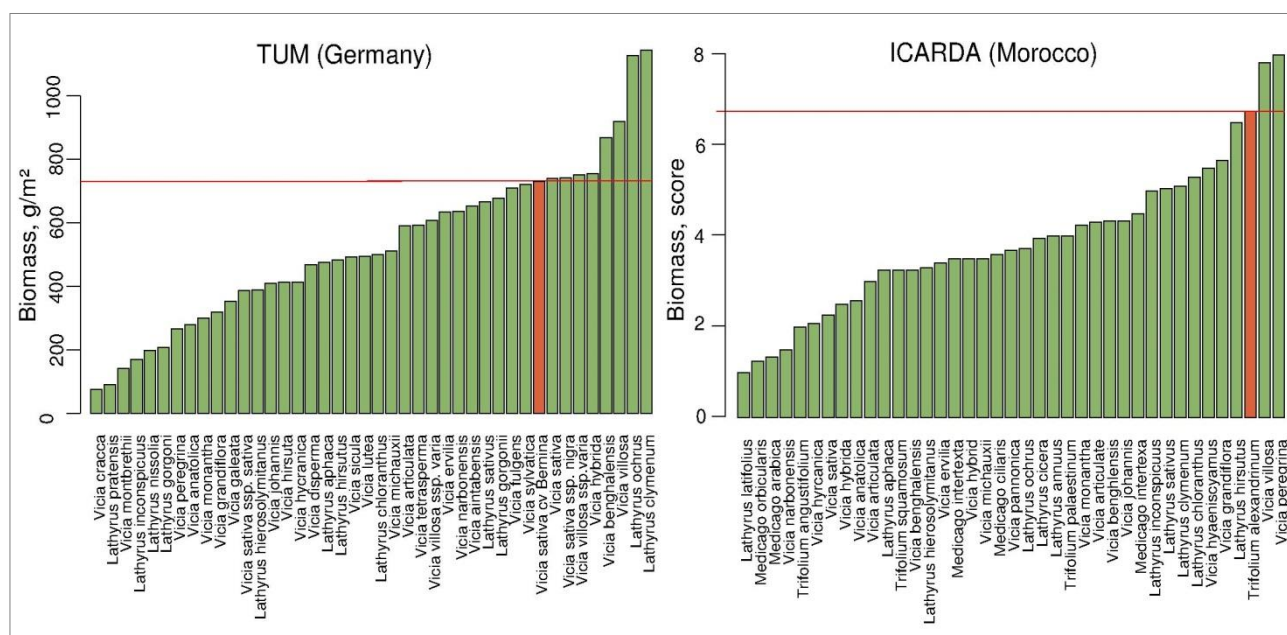


Figure 6. Results of screening experiments in Germany (2015) and Morocco (2013- 2015); mean biomass per species.

Some of the species tested that have never or hardly been cultivated revealed to be surprisingly productive, such as *Lathyrus ochrus*, *L. clymenum* or *Vicia benghalensis* (Figure 6). Several species were in part to be fairly winter hardy and showed a potential as cover crop and green manure crop both in Mediterranean climate and in Germany producing high amounts of biomass and seed. These were prevailing *Vicia* and *Lathyrus* species (Figure 6) of which *V. pannonica* or *V. ervilia* (Figure 7) are already cultivated in certain regions of the world.



**Figure 7** Examples of new potential subsidiary crop species: Flowers of *Vicia pannonica* and *Lathyrus chloranthus*, pods of *Vicia ervilia* and *Scorpiurus muricatus*.

Though the tendencies were similar across testing environments, there were some marked differences. Thus, *L. ochrus* and *L. clymenum* produced most biomass in the trials in Germany, but were among the weaker species in Morocco. On the other hand, *V. hirsuta* was one of the best performing species in Morocco but produced only moderately in Germany (Figure 6). Most clover and *Medicago* species, performed better in Morocco than in Germany. Remarkably, several species performing particularly well under German conditions originated from regions with completely different climatic conditions, such as the southern Mediterranean or Western Asia.

Only a minor part of the non-legume species proved to be suitable as cover crop. In several species, the initial development was slow, in other species, seed dormancy or germinability was limiting. Most species were outcompeted both by subterranean clover and by spring vetch (Figure 8, Figure 9). None of the species seemed to be suitable as admixture to living mulches based on subterranean clover: either the non-legume species was suppressed by subterranean clover or it was too competitive to be used as companion crop for wheat.

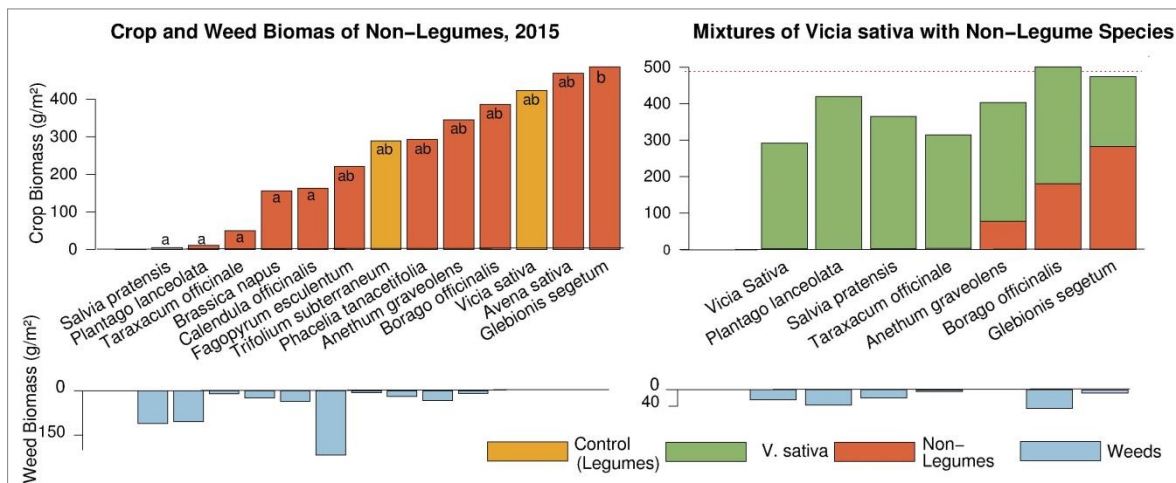


**Figure 8.** Mixtures of *Anethum graveolens*, *Glebionis segetum* and *Borago officinalis* with spring vetch (TUM, 2015).

The early vigor of *Borago officinalis* and *Glebionis segetum* (Figure 8) was remarkably high. Both were very competitive with respect to spring vetch and subterranean clover and produced high amounts of biomass. *Anethum graveolens* was also fairly competitive against weeds, subterranean clover and vetch, although its initial development and shading ability was low (Figure 8). Seed shattering is high in *Borago officinalis* making it a weed and seed production difficult. *G. segetum* and *A. graveolens* are therefore the most interesting species tested here.

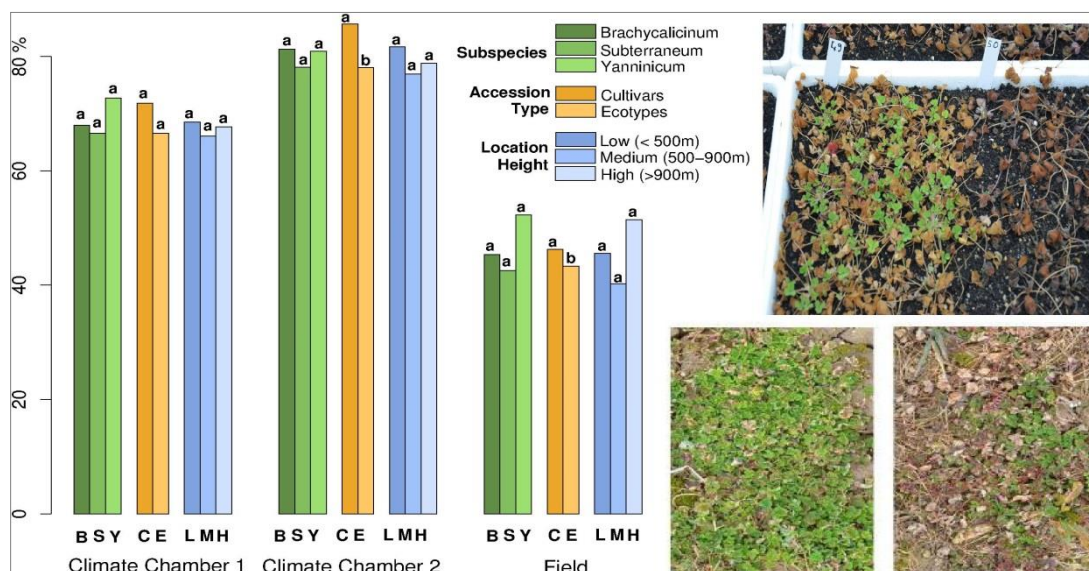
Seed production was very high in the German trials and in Italy while in Morocco it was much dependent on the precipitation in the single years. The highest seed productions were achieved with *Lathyrus ochrus* and *L. clymenum* in Germany, reaching a seed yield level of 300 g seeds/m<sup>2</sup>. However, edge effects on the relatively small plots have to be considered. Seeds of most *Vicia* and

*Lathyrus*-species could easily be harvested with a common plot combine harvester making them attractive for larger scale production.



**Figure 9. Biomass production of non-legumes as sole crops and in mixtures with spring vetch**

Subterranean clover proved to be more frost-tolerant than expected. Most accessions survived all winters in Germany, with snow cover and minimum temperatures reaching  $-15^{\circ}\text{C}$  in winter and also in climate chamber experiments (Figure 10). The ecotypes collected from higher altitudes were no more frost tolerant than the others and the three subspecies did not differ. Commercial cultivars were, however, in average more frost hardy than ecotypes, thus targeted selection for colder climates should be beneficial. Subterranean clover proved not to be suitable for the climatic conditions of Morocco as it suffered from drought stress and the flowering stage was reached too late. No differences among subterranean clover genotypes concerning the aptitude as living mulch could be observed.



**Figure 10 Examples for different degrees of frost sensitivity in the climate chamber and in the field at TUM (percentage of plants killed). The photos show an example in the climate chamber (above) and in the field (2014, below).**

### Potential value of new species as feed or for secondary metabolites

Additionally to weed control, green manure and forage properties, these SC should also have additional functions. Restrictions in use of synthetic antibiotics in livestock production prompted a search for natural components that may exhibit bacteriostatic properties. Such compounds not only

help to maximize animal health and well-being, but may also be potentially useful in controlling emissions of methane and ammonia from animal wastes. Feed values, concentrations of saponins due to their potential detrimental effect on animal health, and of the antioxidants phenolic acids and flavonoids were evaluated in several proposed new cover crops originating from classic forage legume genera: *Trifolium*, *Vicia*, *Medicago* and *Lathyrus*.

There was a high diversity in fat, protein and gross energy contents (Table 3). *Vicia* species contained the highest level of crude proteins. In this regard, of particular interest may be two accessions of *V. villosa*, which had the highest levels of crude protein. Additionally, *V. villosa* accessions had relatively low levels of fat and moderate levels of fiber and ash. Very similar proportions of these components were also observed in other *Vicia* species, mostly in *V. articulata*, *V. sativa*, *V. montana*, *V. peregrina* and also in *V. pannonica*. Aerial parts of all these species have potential for use as a good substrate for protein concentrate production. Among *Lathyrus*, the most important seem to be *L. cicera*, *L. sativus*, and *L. aphaca*. Except for *L. sativus*, which is commonly cultivated in Middle East and Asia and is known to contain the toxic  $\beta$ -ODAP (Oxalyldiaminopropionic acid) in seeds, the other two species will require further toxicological testing, as they may contain unknown levels of  $\beta$ -ODAP in their tissues. Only few *Medicago* accessions had crude protein levels above 20%. Combined with relatively high levels of ash (ranging from 8 to 12%) observed in all *Medicago* accessions, this considerably decreases their feed value. The analyzed accessions of *Trifolium* had the lowest levels of crude protein in their green tissues (11-15%). They also had one of the highest observed levels of crude fiber (32-36%). Dried aerial parts of all tested species can be considered as useful animal feeds with moderately good to very good feed with feed value parameters within the range expected for green forage plants ranging between 12 and 19 MJ/kg, typical for legumes.

**Table 3. Minimum and maximum values for feed values measured in a total of 63 legume species.**

Species	n	Fat (g/kg DM)		Protein (g/kg DM)		Gross Energy (MJ/kg DM)	
		Min	Max	Min	Max	Min	Max
Lathyrus	15	27.3	77.3	144.5	274.9	12.4	19.0
Lupinus	2	51.1	63.6	198.9	232.4	17.1	18.5
Medicago	16	30.7	55.7	145.1	256.2	13.1	17.4
Scorpiurus	1	31.8	31.8	165.4	165.4	16.9	16.9
Trifolium	4	45.5	64.8	111.1	151.6	13.6	16.1
Vicia	25	33.0	62.5	159.9	346.5	15.0	19.1
Total	63	27.3	77.3	111.1	346.5	12.4	19.1

The method developed for analyses of plant secondary metabolites in the OSCAR project is relatively simple and relies on combination of high resolution mass spectrometry for identification of metabolites and charged aerosol detection for their quantification. At this stage, the method is only partially validated, but nevertheless was used to quantify flavonoids glycosides, saponins and phenolic acids in the plant materials.

Diversity of phytochemical parameters among genera, species, and accessions of the same species was high. Contents of flavonoids ranged between 0.9 and 32 mg/g DW in *Lathyrus*, while *Vicia* species generally contained lower amounts of flavonoids (0.2-23 mg/g DW). The only exception was accession #181 of *V. articulata*, which contained nearly 67 mg/g DW of flavonoids. Interestingly, another accession of the same species had only 11 mg/g DW of flavonoids. A large majority of flavonoids from both *Lathyrus* and *Vicia* were derivatives of quercetin, kaempferol and isorhamnetin. Some species also contained myricetin, syringetin and laricitrin derivatives. The flavonoid glycosides were often modified by acylation with phenolic acids, hydroxymethylglutaric acid (HMG) or malic acid. Isoflavone glycosides were not detected in any of analyzed samples from *Lathyrus* and *Vicia*, however their presence was indicated in both *Trifolium* and *Medicago*.



The investigated *Lathyrus* species were generally saponin-free or contained only traces of soyasapogenol B and E derivatives. A few *Vicia* species contained relatively high levels of saponins, both derived from soyasapogenols and other yet unidentified sapogenins. Steroidal saponins, which upon consumption with weed could potentially cause nephro- and hepato-toxic effects in farm animals were not observed in any of the samples. Quinic acid derivatives of coumaric, caffeic and ferulic acids were observed in nearly all species of *Vicia* and in *L. aphaca*. Other *Lathyrus* species contained only trace levels of simple phenolic acids and their glycosides.

### **On-farm trials for mixture optimization**

Trials were conducted in two UK, two German and one Italian farm. Together with the farmers species for mixing were selected and mixtures adjusted over the course of two or three years. Farmers were trained in assessments and joint evaluations took place. Assessments were often difficult for farmers to do and there was a need to adjust them to be robust and simple. Overall, farmer perception even if it was based on less exact assessments corresponded with the general performance as determined by the researchers. Farmers were encouraged by the tested methods to actively engage in selecting species mixes adapted to on-farm conditions and to assess species performance with increased detail and scrutiny. One farmer stated that ‘the process was useful, if nothing else to encourage you to have a closer look at the plants’. Farmer time is a limiting factor when carrying out any on-farm trials and a bias for the least time consuming methods was noted.

## **WP4 Farm technology and machinery**

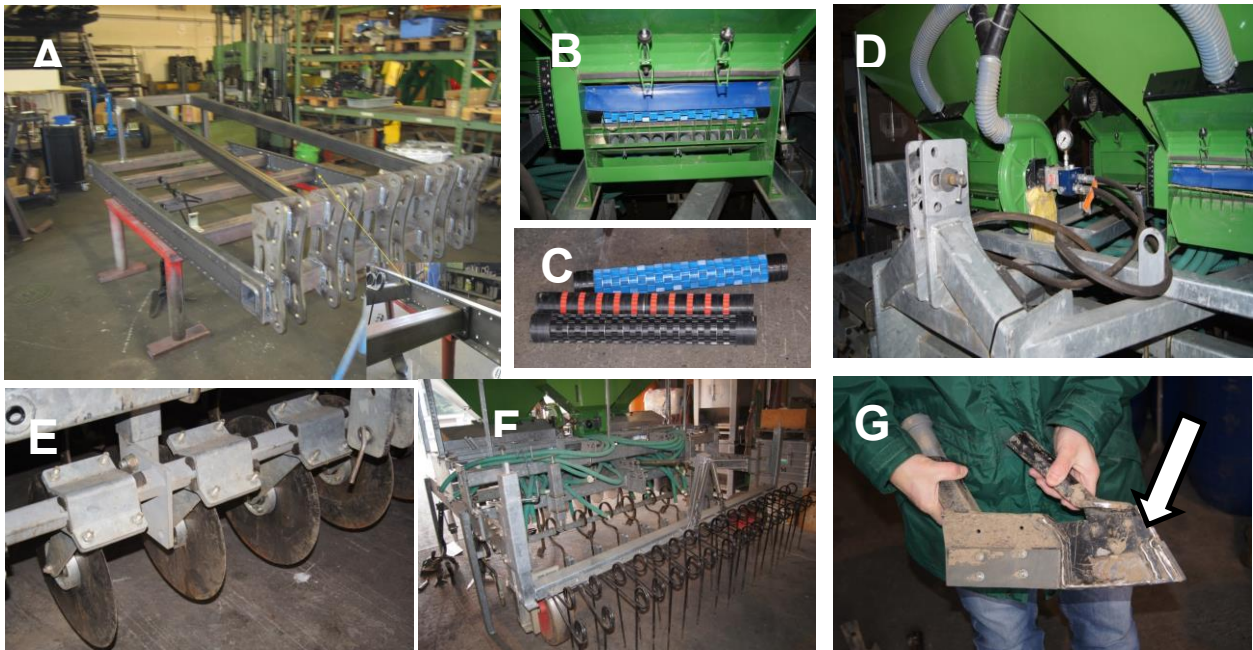
### **The WEco-Dyn Tillage and sowing system**

The machines designed and built within the framework of the OSCAR project were based on the design of the machines developed by Friedrich Wenz in his WEco-Dyn company (<http://www.eco-dyn.de>). After extensive discussion with the potential users and the input of a methodical design approach by Wageningen University where all functionality required for the specific research and testing activities were collected and translated through a so-called “brief of requirements” into a number of possible designs. Realization of the modular concept and assembly of the components started in April 2012. On the basic frame, various soil-engaging tools (chisels, shares, discs) plus the furrow-openers for the sowing coulters can be mounted on the cross-bars (Figure 11). Besides the need of the modular concept, each machine had to be adapted to the available tractors at the experimental sites. The length of the machine allows a layout with wide spacing. The metering system is ground-driven. Seed delivery to the coulters is by air flow.

During the field tests in Poland and after consulting the other partners, it was clear that the sowing units using knife or chisel coulters as furrow openers were not able to perform well in situations with large amounts of moist or wet straw. Secondly, the mechanical drive system for the seed distribution did not function well under the testing conditions (slippage, change in wheel diameter due to soil sticking to tire).

On three machines an electrical drive system for the seed metering devices was installed. This system comprises a central processor with screen/keypad, connected to sensors/actuators on the drill (instrument is also suited for sprayers, harvesters etc.) Since multiple actuators can be installed, it is suitable for steering 2 or 3 metering systems for different seeds. As the system is operating with an accurate Differential GPS, able to reach an accuracy of around 10 cm, the sowing machine can – theoretically – be set up in such a way that seed application can be site specific. Since the metering systems are driven by electrical motors, their rotation speed (=application rate) is independent, but synchronized with, the forward speed of the tractor/machine combination. This system is manufactured by RDS Technology Ltd (UK). This system worked well, eliminating the basic problems with the ground-driven system, but in a set-up with small

experimental fields, the size of the headlands and alleys between the plots is crucial. It takes a minimum of 10 m after the machine starts moving before the GPS system is operational and accurate. For large fields, this will not present any problem.



**Figure 11. A: Basic frame. B: Seed hopper and metering device. C: Easily interchangeable distribution cylinders for various types (sizes) of seed. D: Fan for seed transport by airflow. E: Front-running (straight) discs. F: Example of tine harrow at the rear to close furrows and cover seeds. G: Special design of furrow-opener: the soil will fill up in depression of the blade behind the chisel point (arrow) and therefore eliminates the problem of “smearing” the furrow wall because there is no direct contact between steel and soil**

### ***Typical application, limits and problems***

In 2015, the WEco-Dyn system was used primarily as a sowing machine. In all cases all three hoppers were used for undersowing as well as for sowing of cover crops. Full use could be made from the modular design, e.g.: deep loosening combined with sowing mixtures of cover crops from the 3 different hoppers/metering systems after the clover-grass vegetation. Both the „no-till“ furrow openers and the bounce plate (for broadcasting the seed) were used (Figure 12). Because of the deep loosening, the roots of the cover crops were very well able to penetrate into the soil below. The furrows made by the no-till chisels were filled up with fine soil by the tools at the rear of the machine (Figure 12) and thus created a good structure for the roots to develop.



**Figure 12. Left: Machine equipped with no-till chisels/furrow openers. Front row has narrow cultivator tines. The bounce plates for broadcasting seeds are placed in between the support wheels at the rear, just before the harrow. Right: Machine with discs running in front of furrow openers.**

**Soils with stones and rock fragments.** Small and medium size stones had only minor influence on the quality of the superficial tillage operations. With larger stones or rocks, hydraulic or

mechanical safety devices are required. Under these conditions a complete undercutting by the shares or chisels is not guaranteed.

**Heavy (clay) soils.** Even under dense vegetation these soils can very well be tilled because of the shallow working depth. It is important that the tools are active within the rooting depth of the cover crops. Below this depth, the soil becomes cloddy and soft. In dry soil conditions, penetration of the machine is difficult and it is almost impossible to retain a uniform working depth. The only possibility is to change the soil engaging tools, choosing narrower chisels/shares giving a higher pressure per contact area making it easier for the tools to enter the soil. However, in this case it becomes necessary to apply a second pass to reach a full coverage.

**Light (sand, loamy) soils.** When there is little vegetation cover, superficial tillage is difficult because the soil does not offer enough resistance against the cutting action of the tools, leading to frequent blockages, in particular with straw on the surface. With deeper tillage this does not play a role any more. Wear, however, is quite strong.

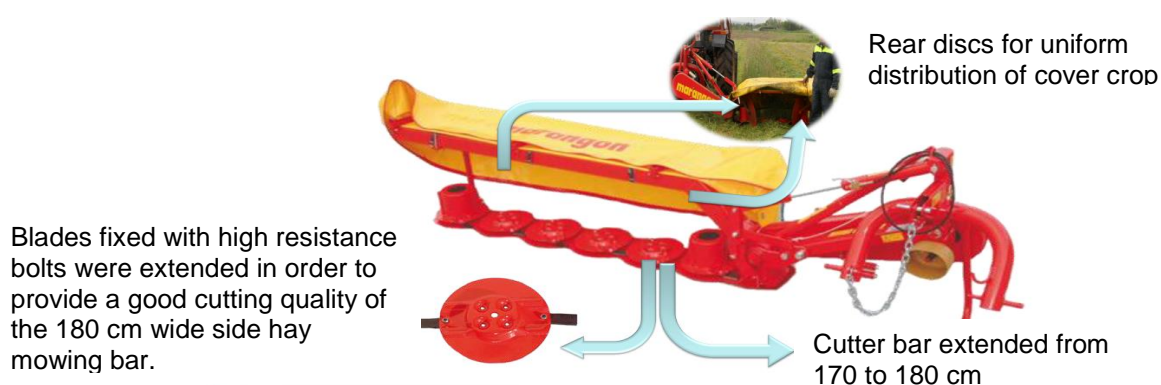
**Wet soils.** In general, these are more difficult to till, particularly when there is organic material at the soil surface. When the chisels are placed close together, blockages will occur easily. When the organic material is long (e.g. stems of cover crops which were not or poorly chopped) a satisfactory result can only be achieved when disk coulters are mounted right in front of the chisels.

**Dry soils.** These generally offer the best working conditions. The only limitation is found with superficial tillage of a very light soil because in such case a „bulldozing“ effect will be seen where the soil together with plant residue is shoved in front of the tools.

**Age / Maturity of the cover crops.** The older the cover crop material is (e.g. mustard after flowering), the softer and weaker the stems are. This usually gives much more difficulty for (superficial) incorporation. Unearthing the crop but leaving it at the soil surface as a preparatory operation is very effective. Whenever possible, the cover crop should be killed and incorporated at the latest at the onset of flowering. When organic material is incorporated superficially as a whole without chopping any subsequent operation can only be done successfully when the chisel-type tools follow disk coulters. If, however, organic material is incorporated superficially after being chopped, then a subsequent (sowing) operation can be done with chisel-type tools without disks, but only when there is enough distance between the soil-engaging tools on the machine.

### Modification of hay mower for arranging cover crop biomass in mulch strips

Vegetable cultivation in conservation agriculture represents one of the main challenges. When plastic mulches are replaced with organic residues deriving from cover crops, the CC aboveground biomass should be placed on the soil surface uniformly in order to provide full soil coverage for the whole season.



**Figure 13. Modifications of the MDN170 cutter**

A conventional hay mower by the Marangon Company was modified for converting cover crop biomass into organic mulch strips. The following modifications were applied: a) a cutter bar was



extended by 10 cm from 170 to 180 cm in order to have a cutter side which met the needs of the transplanter; b) the blades of the disks were extended of 1.25 cm in order to assure a uniform cut; c) a rear double-disc was added in order to distribute the cover crop mulches uniformly across a space of 90 cm. (Figure 13).

### **Development of a no-till transplanting machine for vegetables and tomatoes**

The task of the Ferrari Costruzioni Meccaniche S.r.l. company in the OSCAR project was to develop and implement a system specifically for vegetable production for planting plantlets into thick dead mulch layers without tillage. Various designs were considered. The process involved the development of several prototypes. Important points to consider were methods to reduce the wear and tear due to vibrations, correct row spacing and ability of the machinery to correctly enter the soil without too much weight (Figure 3 lower left). This was achieved with a hydraulic solution.

### **Implements for control of creeping perennial weeds**

Machinery developed by Kvaerneland and “Just Common Sense” were tested extensively. In brief the following conclusions were made about the equipment on perennial weed control:

The selective mower “CombCut” ([www.justcommonsense.eu](http://www.justcommonsense.eu)) has the potential to cut rigid weeds like *Cirsium* spp., leaving the more slender crops undamaged. However, *Sonchus arvensis* and *Elymus repens* are very difficult to cut selectively by the “CombCut” because they are as slender and flexible as the cereal crops. Compared to a non-selective mower no significant differences were found when using the “CombCut” for mowing in autumn.

Two new prototype implements of Kvaerneland, one that vertically cuts shallow growing roots or rhizomes of weeds and another that cuts the roots or rhizomes horizontally, either shallow or deep, were developed during the project period. Both implements cause minimal disturbance of the soil without harmful effects on subsidiary crops. The combination of repeated shoot cutting and crop competition can have a suppressive effect on *E. repens*. A lower cutting height further increases the efficacy of shoot cuttings if they are frequent. However, more research is needed on the factors necessary for rhizome fragmentation to have a directly detrimental effect on *E. repens* or for plant competition and/or shoot cutting to be able to take advantage of the fragmented rhizomes. Promising effects were shown for both implements on *E. repens* and *S. arvensis* when used instead of traditional stubble cultivation in the autumn, and they reduced the risk of erosion. The horizontal root cutter seems to give the same control effects on *C. arvensis* as does deep ploughing. The two new implements are not yet commercially available, but further development is continuing in a new follow-up project.

## **WP5 Soil ecological impact**

### **C and N dynamics, microbial activity and functional diversity**

Dynamics of total organic and total extractable carbon fractions, as well as total N and mineral and microbial N pools were determined for six sites of the MEE1 and MEE2 (SLU, ORC, TUM organic, ART, UNITUS, Morocco) (see Table 1 for details). Total organic carbon (TOC) and nitrogen (TN), nitrate and ammonia content, microbial potential respiration and the activity of several enzymes involved in C, N, P and S cycles were measured in soils from four sites of the MEE representing the principal types of climate (SLU, ORC, ART, UNITUS). Three sampling dates were considered for two years (i) before the beginning of the experiment, (ii), before planting the main crop in the second year, and (iii) after harvesting the main crop. Starting from the second sampling date there were two tillage levels. Soils collected at tillage depth were analyzed since the organic matter deriving from the crop residues changes over time only in the upper soil layer. The Synthetic Enzymatic Index (SEIc) was calculated as the sum of the activity of enzymes involved in the C-



cycle ( $\beta$ -glucosidase,  $\alpha$ -glucosidase xylosidase, cellobiohydrolase). Acid phosphatase, arylsulphatase and chitinase were also determined as enzymes involved in the P- S- and N- cycle, respectively. All enzyme activities were expressed based on soil dry weight and total organic carbon (specific activity). Specific soil enzyme activities were chosen in order to compare various sites with very different soil organic matter content as background value. The microbial functional diversity was expressed in terms of Shannon's Index ( $H'$ ) measured using enzyme activities as reported by (Bending et al., 2002). Soil N and C were assessed in the LTEs of UNITUS and IAPAR after 15 and 26 years, respectively, of conventional and reduced tillage.

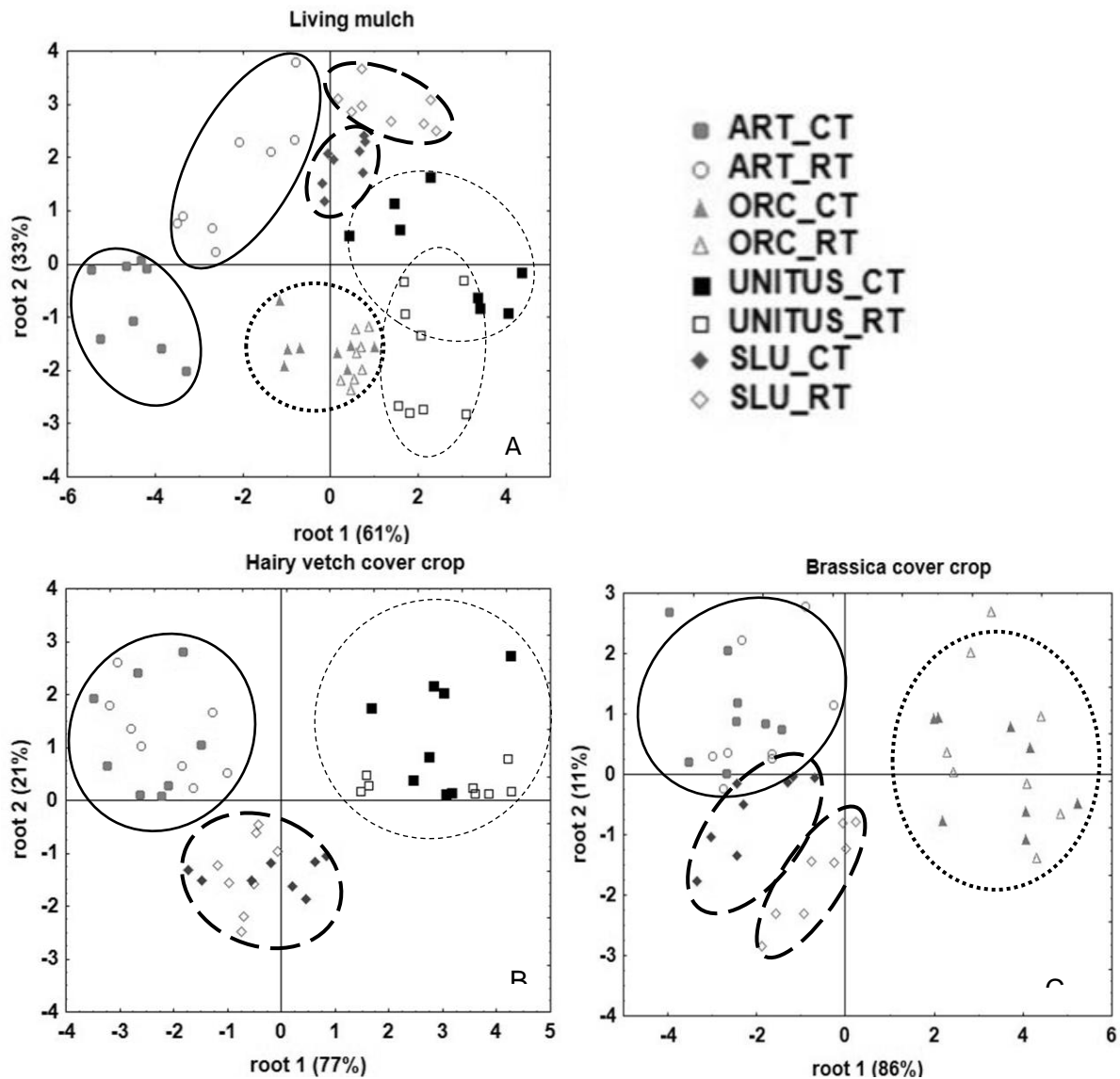
Several soil biochemical properties differed among the two MEEs within sites, probably due to seasonal variation in 2014 and 2015. Tillage effects were less evident than SC effects in all sites in both MEEs. Management effects were minor at the very humid site ART (Table 4). In the other three sites cover crop (CC) and tillage (T) interacted usually for microbial biomass carbon (Cmic) and nitrogen (Nmic) as well as for soil specific enzyme activity (per unit of organic carbon). The functional diversity expressed as Shannon's index ( $H'$ ) was affected by CC at ORC and UNITUS in 2014 but not in 2015 and by T at UNITUS in 2015 (Table 4).

**Table 4. ANOVA of tillage (T) and cover crop (CC) effects on soil chemical and biochemical properties in the four European experimental sites (\*  $p < 0.05$ ; \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$ ) after the main crop.**

Site	Year	Factor	N tot	Corg	C/N	Extr C	Extr N	Cex/ Corg	Nex/ TN	Cmic	Nmic	Cmic/ Nmic	Cmic/Corg	Nmic/ TN	SElc	SElc/ Corg	Chit	Chit/ Corg	Pho	Pho/ Corg	Aryl	Aryl/Corg	$H'$
ART	2014	T				+		+															
		CC							+	+					*	+	+		+				
		TxCC																					
	2015	T															+				*	*	
		CC					+		+	*	+		*	+		+							
		TxCC																					
ORC	2014	T									+					+	+	*		+	*	**	
		CC				*	*	+		**	**	**	**	+			**	*			*	+	+
		TxCC				+		*		**	**	*	**	*	*	*							
	2015	T				+		+				+									+		
		CC				+		+				+			**	*	*	+	**	*	**	*	
		TxCC						*	*		+	*	+	*	*	*	+	+	+			*	
SLU	2014	T								*	**		+	+									
		CC								**	**	+	**	**	*	**	**	**	*	+			
		TxCC								**	+	**	**	+			**	**					
	2015	T					+			**	**		+	+	+						+	+	
		CC					+			**	**		**	**	*	*		*	+	+	+	+	
		TxCC									**			+	+		+	+	+	+	+	+	
UNITUS	2014	T																	+				
		CC					*			**	**	**		**	*		*	*	*		*		+
		TxCC							+	*		+		*	**	*	*	*	+			+	
	2015	T								+	+					+		+		+		+	+
		CC					+			**	*	**	**	+	+	+	*	*	+			+	
		TxCC		*			*			*	*	+		**					*			*	

Discriminant function analysis of soil biochemical properties such as specific enzyme activities and microbial functional diversity expressed by Shannon Index usually grouped three or four sites along root 1 and root 2 ( $P < 0.05$ ; squared Mahalanobis distances between groups) (Figure 14). The specific activity of enzyme involved in C (SElc) and N (chitinase) cycles were positively correlated with root 1 and negatively correlated with root 2 in the living mulch plots (Table 5). Therefore, specific activities of SElc, chitinase, acid phosphatase and Shannon's index distinguished the sites mainly along root1; while tillage treatment at each site was distinguished along root 2 by enzyme activities. Conversely, for hairy vetch and brassica CC the soil biochemical

properties distinguished only the experimental sites while the two tillage levels were not separated at any site with exception of brassica CC at SLU. These results allow for soil and climate dependent predictions about the effects of SC based farming practices.



**Figure 14. Discriminant Function Analysis (DFA) among different European experimental sites using specific enzyme activities (per unit of organic C) and Shannon Index in conventional (CT) and reduced (RT) tillage of each subsidiary crops (living mulch A, hairy vetch B and Brassica C) (see table 1 for site details).**

**Table 5. Correlations among the roots of the DFA shown in Figure 14.**

	Living mulch		Hairy vetch		Brassica	
	root 1	root 2	root 1	root 2	root 1	root 2
<i>Specific enzyme activity</i>						
SEIc	.511***	-.661***	.569***	.310*	.877***	ns
Chitinase	.599***	-.537***	.795***	ns	.886***	-.298*
Acid Phosphatase	.669**	ns	.513**	-.368**	.390**	-.717***
Arylsulphatase	ns	-.348**	ns	ns	.614***	ns
<i>Microbial functional diversity</i>						
Shannon's index H'	-.293*	ns	-.315*	ns	ns	ns

Soil nitrate was overall low and varied little among treatments. The only cases with a leaching risk as indicated by soil nitrate contents over  $30 \text{ mg N-NO}_3 \text{ kg}^{-1}$  were with leguminous and brassica CC at ART where fertilizers had been applied and leguminous CCs in Morocco (data not shown). Nitrate levels were very low at ORC, suggesting low nitrification rates at that site.

The microbial activity measured in terms of specific enzyme activity (per unit of organic carbon) in soil under leguminous CC and LM showed a higher median and a wide range of values, from 50 to  $250 \text{ nmol MUF mg C}^{-1} \text{ h}^{-1}$ , at UNITUS (North Mediterranean). The lowest specific activity was registered at ART (continental) ranging from 28 to  $100 \text{ nmol MUF mg C}^{-1} \text{ h}^{-1}$ , followed by SLU and ORC (Nemoral and oceanic, respectively). Moreover, the soil under leguminous living mulch showed a lower median value of specific activity than leguminous cover crop at UNITUS (in CV 160 vs. 145 and in RT 150 vs.  $130 \text{ nmol MUF mg C}^{-1} \text{ h}^{-1}$ ) and ORC (in CV 140 vs. 110 and in RT 130 vs.  $120 \text{ nmol MUF mg C}^{-1} \text{ h}^{-1}$ ). These results suggest that in Mediterranean and Oceanic climatic zones, the organic substrates released by leguminous CCs are more hydrolysable than those released by leguminous LMs.

In the long term experiment in Brazil, stocks of total, particulate, and mineral associated organic carbon were significantly higher under no tillage in the top soil layer 0-10 cm, probably as the result of plant residues providing soil cover combined with lack of soil disturbance. On the other hand, in the 10-20 cm soil layer, carbon contents were higher under conventional tillage (data not shown). Soil aggregate stability was increased and leaching problems close to nil under long term minimum tillage. Data were consistent with previous publications (Calegari et al., 2008).

### **Impact of different CC and LM based cropping systems on the abundance and ecological function of arbuscular mycorrhizal fungi (AMF).**

Both tillage and presence and type of subsidiary crop had no effect on the AMF spore abundance in the short term of the MEEs. In contrast, in the long-term experiment run by UNIP and SSSA in central Italy for more than 20 years, both application of minimum tillage systems and reduced use of nitrogen fertilizers increased the spore populations in the soil significantly.

Roots of subsidiary crops and following main crops were collected in the MEEs in Switzerland and in Italy (UNITUS) and AMF root colonization assessed. Also, the contribution of AMF to soil P uptake was assessed using nylon bags with different mesh sizes that were either accessible to bacteria only ( $0.1 \mu\text{m}$  mesh size), bacteria and soil fungi including AMF ( $30 \mu\text{m}$  mesh size) and roots, fungi and bacteria ( $1000 \mu\text{m}$  mesh size).

Cover crops black oat (66%), subterranean clover (64%) and hairy vetch (59%) were well colonized as expected, the cruciferous cover crop species, oilseed radish (0.4%), was not able to sustain AMF. One month after sowing, maize roots at ART were more colonized when preceded by the mycorrhizal CCs than by brassica. For tomatoes at UNITUS the effects were less clear (data not shown). Tillage had a significant negative impact on AMF root colonization of the main crops at both locations. This confirms that not tilling the soil allows for a better colonization of the next crop from the undisturbed AMF mycelium network. With the mesh bag method, we could estimate that approximately 25% of soil P uptake was taken up by AMF and potentially transferred to the plants into field conditions. When looking at the experimental factors, we observed that AMF and plant P uptake are generally higher in no tilled plots compared to the plough treatment.

### **Aggregate stability, ground cover and erosion risks**

In five of 10 sites where the MEEs were conducted no-till systems increased soil aggregate stability. These were temperate and Mediterranean environments. In contrast, in climates with a shorter growing season, such as the northern countries and Morocco no effects were found in the

short term of the MEEs. Except for TUM in southern Germany in 2014, where subsidiary crops were particularly well developed, no effects of subsidiary crops or effect of interactions between subsidiary crops and tillage system on aggregate stability was observed. Thus, erosion risk can best be assessed through soil aggregate stability

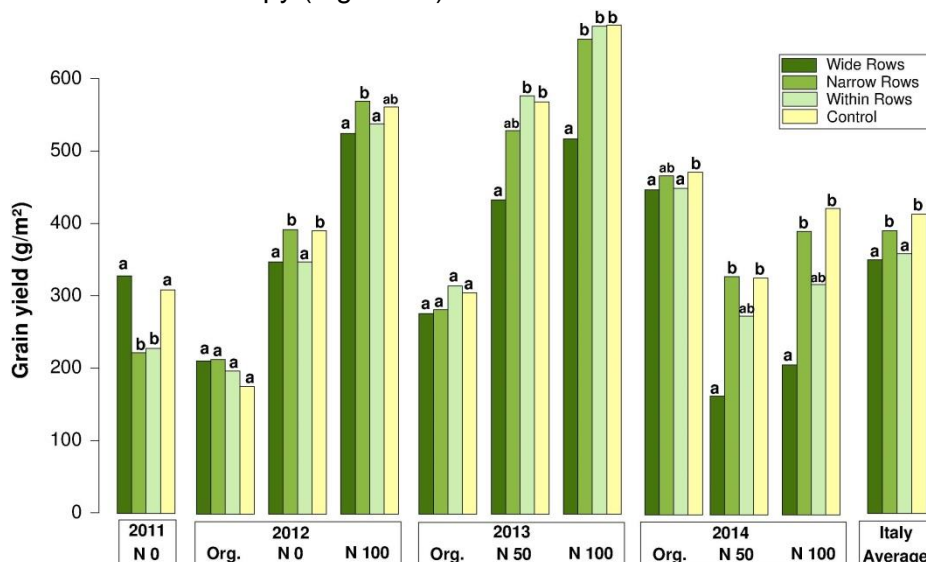
Establishment of a living mulch in most places contributed only little to ground cover during the growing season. Only in Germany (TUM) and in central Italy (UNITUS) where subterranean clovers established well, an increase in cumulative ground cover duration could be detected. Living mulches as undersown subsidiary crops at these sites were most effective since no fallow period occurs between harvest of the main crop and establishment of the subsidiary crop and problems of establishment of CCs e.g. during dry summers are avoided. The protective effects of intercalary cover crops depend on fast establishment and complete ground cover before slowing down growth in winter. Thus, in Mediterranean climates, living mulches may be the better option.

## WP6 Methods for regulating competition and perennial weed control

### Management factors affecting competition among main crop, LM, and weeds

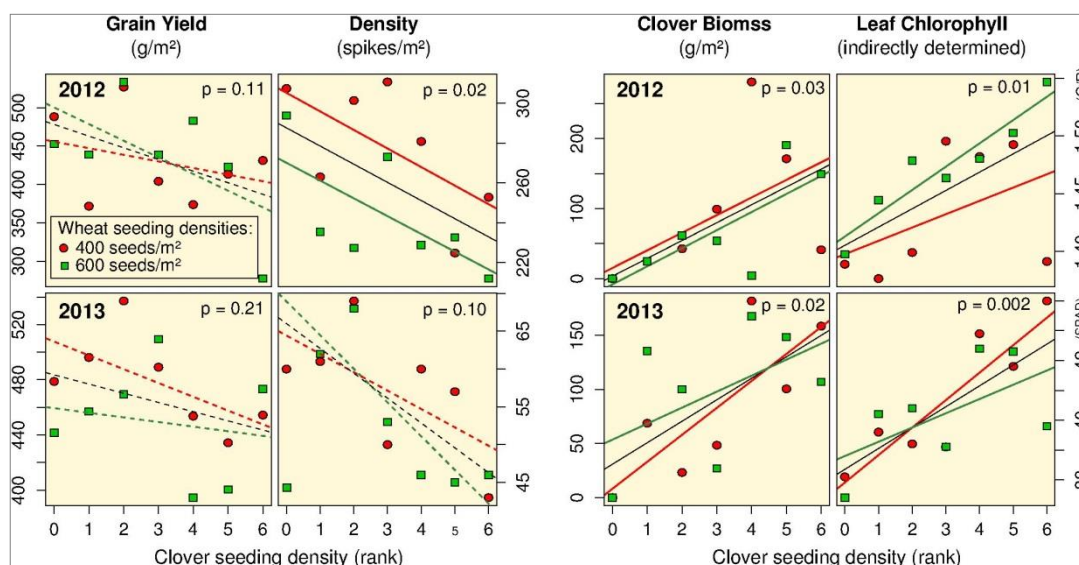
In SC based systems, there are three plant groups competing for similar resources: main crop, subsidiary crop and weeds. The LM competes with the main crop, and both together compete against the weeds. In a comprehensive set of over 40 experiments conducted mostly at TUM, the most important agronomic factors influencing competition in LM based systems were investigated of which the main factors investigated are presented.

**Spatial arrangement:** Narrow alternate rows that are closest to a uniform seed distribution, were most advantageous, both for wheat yield and the development of the subterranean clover canopy independent of cropping system and N-fertilization levels. Wide rows allowed for good subterranean clover development, but wheat density and consequently yield was reduced, while mixing clover and wheat within rows led to increased competition from the beginning and weaker development of the clover canopy (Figure 15).



**Figure 15** Effect of seed arrangement of wheat and subterranean clover on grain yield at TUM, 2011-2014; Wheat was grown alone or as within row mix with clover with 15 cm row spacing (control, within row) or with the clover with wide row arrangement (double rows of wheat with 10 cm distance with 35 cm distance between double rows where clover was sown) or narrow row spacing (two rows of wheat and one of clover with regular 10cm spacing). Org: Experiments with organic management; "N 0"—"N100": conventional management with different levels of N fertilization. Bars with different letters are significantly different according to Tukey's HSD-Test ( $p < 0.05$ ).

**Sowing density:** Higher densities of subterranean clover increased clover biomass, decreased wheat density (though the yield was not significantly affected) and increased leaf chlorophyll and, thus, protein content. This was observed several times in the experiments at TUM (Figure 16). Measurements of the  $^{15}\text{C}$  content (data not shown) revealed that a part of the nitrogen had been transferred from legumes to wheat.



**Figure 16. Effect of sowing densities of clover and wheat on grain yield, spike density, clover biomass and SPAD readings. P-values refer to the effect of clover density.**

**Seeding date:** If clover is planted after wheat, wheat has a competitive advantage and vice versa. Seeding wheat later relative to clover decreased grain yield and increased clover biomass but had no significant effect on grain protein content.  $^{15}\text{N}$  abundance, again suggested transfer of previously fixed nitrogen from legumes to wheat (data not shown).

**N-availability effects:** In an experiment with 12 different levels of N fertilization in a mixed canopy of subterranean clover and wheat higher levels of N fertilization increased wheat yield and biomass, and reduced biomass of clover. At the highest levels of N fertilization (producing yield levels of more than  $7 \text{ t ha}^{-1}$ ) little clover was present indicating that the limit to establish a clover canopy is a yield level around  $6\text{--}7 \text{ t ha}^{-1}$  for wheat.

**Genotypes of wheat and clover** interacted somewhat and there may be an option for selection of clover genotypes with improved suitability as LM. With the currently available genotypes in most experiments there was little or no yield decrease due to the presence of associated clover and positive effects on soil quality may compensate for minor yield losses.

## Weeds in the MEEs

The dominating annual and perennial species in the MEEs were related to the pre-crops and pedoclimatic conditions with no general pattern. The initial seed bank in the organic system at KU was analyzed in detail and was larger and more diverse than what is reported from conventional systems in transition due to the herbicide free system.

Subterranean clover as living mulch in wheat overall did not confer weed control. Weed density and biomass were significantly higher in LM plots and wheat yield was negatively correlated with weed density ( $r^2=0.25$ ,  $p<0.001$ ) and weed biomass ( $r^2=0.16$ ,  $p<0.001$ ). In contrast, cover crops competed well with weeds in the intercrop period. All treatments with cover crops had significantly ( $p<0.001$ ) less weed biomass in spring compared to the control treatments (bare fallow).

Before weed control, mean number of weeds in maize was higher in the ploughed systems (ANOVA,  $p < 0.1$ : plough 52 plants  $m^{-2}$ ) than in reduced tillage (44 plants  $m^{-2}$ ) or no tillage (24 plants  $m^{-2}$ ). This is related to the larger amount of soil being mixed and consequently seeds exposed to germination conditions in the deep tillage. However, tillage effects also interacted with the CCs used. Thus, legume cover crops tended to increase weed density, mostly when CC biomass is incorporated by tillage (plough or WEco-Dyn). N released from the legume CC is not only readily available for the main crop but also for weeds. Weed control without ploughing and/or the use of herbicides was a major challenge in the MEEs. Reduced tillage with the WEco-Dyn resulted in higher weed biomass (ANOVA:  $p < 0.01$ ) after weed control operation in the maize crop (ANOVA:  $p < 0.01$ ). Control of problematic perennial weeds (e.g. couch grass or creeping thistle) is difficult.

Data from the LTE at IAPAR in Brazil show that after 29 years of minimum tillage, soil cover by CCs was usually more than twice as high in no-till compared to conventional tillage. In contrast, soil cover by weeds in no-till was about 15% compared to 39% under conventional tillage during the CC period. Main weed under no-till was rye-grass, under conventional tillage corn spurry (*Spergula arvensis*). Grasses are known to be more problematic under no-till.

### Mowing and innovative tools for perennial weed control

New implements have the potential to reduce the density and growth of perennial weeds using CC management without soil cultivation. Series of experiments were performed on mowing methods (above ground weed control) and on mowing combined with rhizome fragmentation (below ground weed control) to control *Elymus repens*, *Tussilago farfara*, *Cirsium arvense*, and *Sonchus arvense* in Norway and Sweden. Innovative machinery by the company Kvaerneland including a horizontal and vertical root cutter (Figure 17) and the selective cutter “CombCut” were tested among others. Traction requirement of the horizontal root cutter was reduced with ca. 40 % compared with plough (both used at 20 cm soil depth).



**Figure 17. Left: vertical and right: horizontal root cutter prototypes by Kvaerneland company**

**Control of *C. arvense*:** The horizontal root cutter can replace deep ploughing in spring. There were no additive effects of combining shallow horizontal root cutting and deep ploughing in spring. Selective (in crop) management gave promising result the first year but not the second year. This treatment was, however, detrimental for the crop yield. The method must be modified e.g. by combining with increased row distance and place for the tractor wheels between crop rows for preventing crop damage. Using the horizontal root cutter for black fallow gave the most promising results when combining cutting at 10 cm and 20 cm soil depth. The root cutting may be combined with mowing the thistle plants especially in wet conditions. In green manure leys combining root cutting and mowing gave best control.

**Control of *E. repens*:** Despite both shoot cutting/mowing and clover competition strongly suppressing *E. repens* biomass production and carbohydrate reserves, there was little evidence of any added benefit from combining these factors with rhizome fragmentation, except in situations where rhizome fragmentation had a detrimental effect on *E. repens* on its own. Thus, the effect would be additive rather than synergistic. In fact, when combined with only shoot cutting the



carbohydrate reserves in the shoots drained proportionally faster in the larger rhizome pieces than the smaller ones. This effect disappeared when combined with both shoot cutting and clover competition however. Overall, repeated and low cutting proved most effective.

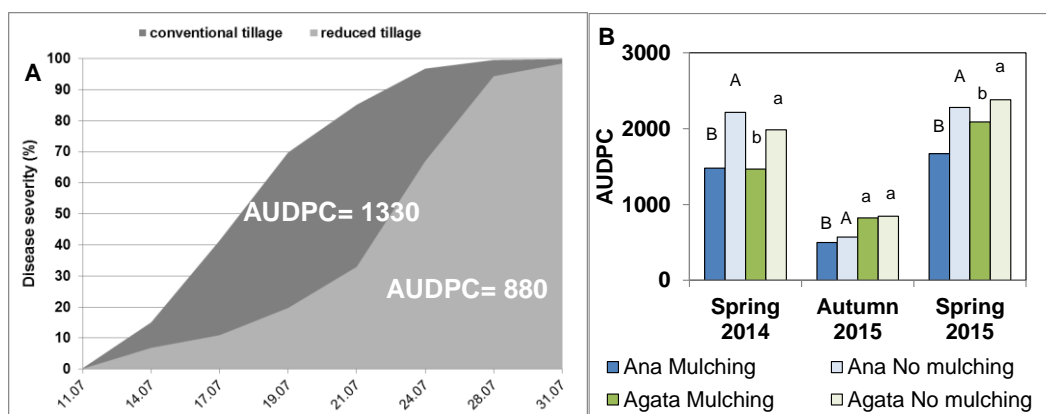
## WP7 Phytopathological risks and solutions

### Air- and soilborne disease dynamics in CC and LM systems with different tillage strategies

Foliar and foot diseases were assessed in the MEEs of SLU, KU, TUM, ART, UNITUS, ICARDA, and INRA and in the different LTEs (see Table 1 for partner details). Overall disease severity on all crops assessed was low, due to low pathogen pressure and/or unfavorable weather conditions for disease development. Some general observation suggest that the systems tested either result in no changes in plant health or may improve plant health. Thus, introduction of leguminous plants as cover crops or living mulch did not increase foliar or foot diseases of main crops in the MEE's. Decreases with cover crops were observed in Sweden on wheat foliar diseases and on stalk rot in Brazil. Fertilization with nitrogen had a tendency to increase severity and incidence of foliar diseases, however even then damage on the crops was low and had no biological importance. Foot and root rot on the SC's was low to moderate and depended more on the weather and site conditions than on the experimental treatments. Therefore, the use of SCs can be encouraged.

Effects on nematode communities in the MEEs were highly variable with a tendency of SC based systems to favor more generalist nematodes. In the LTE at IAPAR, however, use of CCs shifted nematode communities towards those present in more stable soil ecosystem.

Tillage intensity had no clear effects on the incidence and severity of diseases and depended highly on the site and year with no significant increase due to reduced tillage in any of the experiments. At KU in the potatoes in 2014, in the reduced tillage treatment that also received dead mulch, late blight (caused by *Phytophthora infestans*) was delayed five days compared to plots that were ploughed and not mulched. Overall, the area under the disease progress curve (AUDPC) was reduced from 1330 in the ploughed treatment to 880 in the treatment with reduced tillage ( $P < 0.01$ ) (Figure 18A). No late blight occurred at KU in 2015 leaving these data as single event without repeat. However, mulching also led to reductions in potato late blight under subtropical conditions in three different experiments at IAPAR in southern Brazil (Figure 18B).



**Figure 18. A: Disease progress over time in % disease severity and area under the disease progress curve (AUDPC) of late potato blight in 2014 at KU. B: AUDPC of late blight in Brazil on two varieties in three experiments with and without mulching. Significant differences between mulch and no mulch within variety are shown by different upper case letters (Ana) lower case letters (Agata).**

### Effects of LM and CCs and improved soil management on system health

Biofumigation with was studied at SLU with a high glucosinolate producing oilseed radish (*Raphanus sativus* var. *oleifera*) as cover crop before maize in the field and in the laboratory. Maize plots were inoculated with *Fusarium graminearum* and *F. culmorum*, however, disease pressure was low as shown by low levels of fungal DNA contents in the plants and no effects of the oilseed radish on disease could be seen in the field. In the laboratory, growth of both *F. culmorum* and *F. graminearum* was influenced by volatiles produced by plant material of *R. sativus*. Only the volatiles produced from root material had a significant effect on the hyphal growth whereas the effects of shoot material were similar to those of the control treatments (water or rye). The effects of *R. sativus* roots were not as strong as those of *B. juncea* plant material (data not shown).

The potential of various yard waste composts (added in the amount of 20 % v/v to the growing substrate) to suppress soil-borne pathogens and the contribution of compost biological attributes to disease suppression using gamma sterilized compost were tested on peas as model plants in greenhouse experiments at KU. Pathogens *Fusarium avenaceum*, *F. solani*, *F. oxysporum*, *Didymella pinodes* and *Phoma medicaginis* were used as they are the most important soil borne pathogens of the legume foot and root rot pathogen complex in Germany. Inoculation was done by watering pots right after sowing with suspensions of  $2 \times 10^4$  spores g<sup>-1</sup> of substrate. Plants were harvested after 4 weeks. In addition, soils of the MEE fields at KU that had different histories of compost amendments and tillage practices were collected in 2014 and 2015, respectively, after incorporation of summer vetch to test for their suppressiveness to diseases.

Compost effect on disease severity and fresh weights of pea plants was highly variable and depended on pathosystem, its age and substrate composition. Yard Waste Composts (YWC) were the most effective in suppression of disease caused by *F. avenaceum*, and much less so with respect to the other pathogens. After gamma irradiation the suppressive effect of compost was completely lost in both pathosystems demonstrating the biological nature of disease suppression.

The disease index (DI) in the un-inoculated MEE field soils that had been ploughed was 42 and 45 without and with a history of compost addition, respectively while in the WEco-Dyn soils it was 38 and 27 without and with compost, respectively indicating high initial pathogen pressure in the soil. The differences among tillage treatments were not statistically significant. Inoculation with *F. avenaceum* or *P. medicaginis* did not increase disease nor the interactions with the soil (Data not shown). Mean biomass in WEco-Dyn tilled field soil was 1.04 and in ploughed soils 0.73 g/plant. The highest biomass per plant was produced in soils coming from the un-inoculated WEco-Dyn tilled field soils (1.21 g/plant). In contrast, plants grown in soils from ploughed plots produced the highest biomass in the treatments where compost was applied (0.8 g/plant). These trends, albeit not statistically significant, indicate that even at an early stage after changing tillage systems effects on soil suppressiveness may become visible.

### Susceptibility of LM and CC species to soil-borne pathogens

Members of about 15 genera, 40 species and more than 100 accessions were obtained from TUM and INRA Morocco for resistance testing. While 109 accessions germinated only 62 produced enough seedlings to allow for screening for susceptibility to *Fusarium avenaceum*, *F. oxysporum*, *F. solani*, *Phoma medicaginis* and *Didymella pinodes* in a series of seven successive experiments. Inoculations were done as described above with spore solutions at transplanting into sterile sand.

Incidence of seed-borne infections was high in *T. subterraneum*. This could pose additional problems in practice as there are very limited options to treat the seeds. The two pea controls behaved as expected with Santana uniformly susceptible to the pathogens tested and EFB33 considerably more resistant (Table 6). Results showed that most of the plant species and



accessions tested were highly susceptible to *F. avenaceum*, with notable exceptions of *Crotalaria ochroleuca*, *Lotus pedunculatus* and a few *Trifolium* and *Medicago* accessions (Table 6). *F. oxysporum* caused variable disease severity on some *Trifolium* species, otherwise, infections were low, while *F. solani* caused overall higher disease severity with some variation among accessions. *P. medicaginis* and *D. pinodes* most severely affected *Lathyrus* accessions; otherwise infections were low with *D. pinodes* appearing to be more specific.

**Table 6. Disease severity (1 – healthy, 9 – dead plant) on different legume genera inoculated with five pathogens. Numbers in parentheses show minimum and maximum values for each genus. Number of species per genus tested is given as n value.**

Genus	<i>D. pinodes</i>	<i>F. avenaceum</i>	<i>F. oxysporum</i>	<i>F. solani</i>	<i>P. medicaginis</i>
<i>Lathyrus</i> (n=9)	4.4 (2.0-6.0)	7.9 (6.5-9)	3.6 (1.2-4.8)	4.4 (2.8-6.0)	4.6 (1.4-6.8)
<i>Medicago</i> (n=8)	1.7 (1.0-2.7)	4.4 (1.0-7.3)	2.0 (1.0-3.3)	2.7 (1.0-4.4)	2.1 (1.0-4.2)
<i>Trifolium</i> (n=26)	2.1 (1.0-5.8)	3.2 (1.0-8.2)	2.0 (1.0-5)	2.4 (1.1-5)	2.0 (1.1-5.4)
<i>Vicia</i> (n=13)	2.3 (1.0-3.4)	7.8 (6.6-9)	2.2 (1.0-3.0)	3.1 (1.2-4.6)	2.6 (1.2-4.6)
<i>Melilotus</i> (n=1)	2.3	5.2	3	5.8	3.8
<i>Scorpiurus</i> (n=1)	3.8	5	3.2	6.4	3.3
<i>Crotalaria</i> (n=1)	3.8	1.8	2	5	1.8
<i>Galega</i> (n=1)	2.4	9	1.6	2.4	4.2
<i>Santana</i>	5.3 (4.0-6.0)	6.0 (3.0-7.0)	4.3 (3.0-5.0)	5.3 (4.0-6.0)	4.8 (4.0-6.0)
<i>EFB33</i>	3.6 (2.0-5.0)	4.1 (2.0-7.0)	2.4 (1.0-4.0)	4.5 (2.0-6.0)	3.4 (1.0-5.0)

Effects on plant biomass followed a trend similar to the disease severity symptoms with high variation among species and accessions of the same species (data not shown). The strongest negative effects on the fresh weights were measured for *F. avenaceum* inoculated plants with up to 100% biomass reduction (*Lathyrus inconspicuus* L1672 and *Vicia hirsuta* 1536). However, in some *Trifolium* accessions inoculation with *F. avenaceum* even increased fresh weights.

## WP8 Cover Crop and Living Mulch Toolbox

The Cover Crop and Living Mulch Toolbox summarizes results of the OSCAR project. The Toolbox has been developed by the Organic Research Centre (UK), together with the Technical University of Munich (Germany), who gave technical assistance and led the development of the cover crop database. All OSCAR partners contributed to the development of the Toolbox.



**Figure 19. The home page of the Cover Crop and Living Mulch Toolbox (www.covercrops.eu).**

The Toolbox is presented as a series of web based tools (a Wiki; a Decision Support Tool; and a Species Database) to help improve knowledge and drive the use of CA practices and subsidiary cropping systems throughout Europe. The content draws on scientific literature, technical information and results from the main research element of the OSCAR project; a series of coordinated field trials of cover crop and living mulch species in 12 different environments. The Toolbox also presents the results of the OSCAR screening trials aimed at identifying novel species and genotypes for use as cover crops or living mulches. Accompanying the Toolbox the OSCAR

Project Facebook page ([www.facebook.com/The-OSCAR-Project-643571612380744/](https://www.facebook.com/The-OSCAR-Project-643571612380744/)) has up to date information on related events, news items and links to relevant reports from other projects.

The Cover Crop and Living Mulch Toolbox is available at: [www.covercrops.eu](http://www.covercrops.eu).

## Concluding remarks

In all trials, wheat yields were usually slightly inferior in the presence of living mulch (LM). This was driven by lower crop densities due to the wider row distances used in the common field trials. For successful LM based cropping high crop densities are needed and more equal and regular sowing patterns were best suited. Wheat is particularly suitable to be grown with a companion crop, because its canopy is not completely closed. In systems with expected yields  $\leq 7 \text{ t ha}^{-1}$ , a clover canopy that is sufficiently strong to generate a dense sward after main crop harvest may co-exist. In some cooler places sowing the LM before the main crop can be successful, however, competition needs to be managed. In contrast, undersowing in spring in colder areas generally will not lead to competition by the LM as it will only start growing strongly after the main crop is harvested. This practice leads to early development of a cover crop (CC) where little time is available after wheat harvest, improves weed suppression and saves energy. LM performed best in temperate and Mediterranean North environments where winters are relatively mild and competition for water is not limiting wheat productivity and simultaneous sowing of wheat and LM can be practiced. LMs are thus of particular interest for organic farming, but might also be of interest for the more extensive conventional farming systems in Europe.

Not surprisingly, in the first year of reduced tillage (RT) development of the spring sown main crop was weaker and weed pressure was higher. CCs could compensate these effects depending on their biomass and ground cover dynamics that both have to be maximized to suppress weeds. Again, temperate and Mediterranean North climates are optimal for CC development. Clearly, the challenge of obtaining satisfactory weed control without using herbicides generally increases in reduced tillage. Especially further north, where the growing season is shorter, it is necessary to develop new methods for weed control in spring and autumn. Mechanical tools for subsidiary crop suppression, such as the roller-crimper work best during flowering of the CCs. Thus, spring crops should be established as late as possible after the CC. In dryer conditions dead mulch is very beneficial and water availability has to be balanced against the SCs benefits. Long-term effects of RT either did not affect or overall benefited yields and reduced weeds. These were particularly pronounced in the sub-tropical climates in southern Brazil.

Some positive soil ecological impacts of RT compared to conventional tillage (CT) were increased aggregate stability, higher soil C contents, higher microbial activity, and increase of arbuscular mycorrhizal fungi (AMF) survival. These were greater in leguminous LM than CC systems in all but the oceanic climatic zones while for brassica CCs RT was most positive in the continental site where the climate is very humid. Nitrate leaching only played a role under north Mediterranean conditions or when in addition to SCs also nitrogen fertilizers were applied. We could show that CCs are an important management tool to sustain arbuscular mycorrhizal fungi (AMF) during fallow periods and for improved colonization of succeeding crops. In P-non-limited systems AMF did not increase yields of main crops. However, a major AMF contribution to soil P uptake of about 30% was measured. This ecological function was greater in RT than CT.

Despite the fact that overall disease severity on all crops assessed was low, due to low pathogen pressure and/or unfavorable weather conditions for disease development some general observation suggest that RT, LM, and CC based systems either result in no changes in plant health or may improve plant health. Introduction of leguminous plants as CC or LM did not increase foliar or foot diseases of main crops in the field. In the reduced tillage treatment of potatoes that also received dead mulch, potato late blight was significantly reduced in the year when late blight

occurred in Germany and in three consecutive trials in Brazil. Disease severity of pea plants grown in soils collected from field trials that had received compost during two years under CT or RT was only little affected. There is a need to continue the management for longer before making final conclusions. Laboratory and greenhouse trials confirmed the potential of volatile and water soluble compounds from *R. sativus* roots (but not aboveground plant parts) to reduce hyphal growth of both *F. graminearum* and *F. culmorum* and the potential of compost to suppress foot and root rot diseases of peas depending on compost type, age, and pathosystem. Biological properties of compost were most important for disease suppression.

The modular structure of the WEco-Dyn machines allows a wide range of possible applications, from clean soil tillage (no crop residues left on the field surface) including the preparation of a seedbed, up to minimum and no-tillage systems with respect to pre-sowing operations. Normal sowing (in a clean seedbed), sowing in mulches and sowing in undisturbed soil is possible. However, the field practice has shown that the users in general were not always able to benefit from all the options, simply because there were so many. This often led to sub-optimal settings of the machine in view of the field conditions and therefore the results did not meet the expectations. Clearly, there is a need for in-depth technological support for farmers willing to change to RT.

For the optimal formation of dead mulch layers and direct planting of vegetables into these, the machinery is ready for use. However, costs of the transplanter seem too high for economic competitiveness despite the large advantage of this method.

For the control of perennial weeds, rhizome-root fragmentation was shown to be a less intensive control method compared to soil tillage and should be combined with other direct and preventive measures against such weeds in a multifaceted strategy. Improvements in both technical and holistic strategies are needed especially with respect to effects of timing on below-ground bud sprouting and dormancy.

The range of subsidiary species can be drastically improved. Selection of suitable ecotypes/accessions may be a useful breeding strategy in the short term since many unselected accessions performed as well or better than the standard cultivars. However, new legume and non-leguminous species of interest also emerged and their potential should be further evaluated. There was overall a high variability in the susceptibility/resistance of different legume species as well as accessions of the same species. This suggests differentiation and thus selectability for resistance. With exception of *F. avenaceum*, accessions of *Trifolium repens* were resistant to the tested pathogens. In contrast, accessions of *T. subterraneum* exhibited moderate to severe symptoms of diseases. Resistant accessions of different species identified in the OSCAR project could be valuable genetic material for future breeding programs aiming at the development of resistant and tolerant varieties of small grain legumes to important soil-borne pathogens. The best accessions of the most promising species are currently being propagated in order to obtain larger quantities of seed, which will be used for on-farm testing in the near future.

The economic analyses showed a surprisingly wide range of potential outcomes of RT and SC based cropping systems even in the short term. The analyses were much more robust for the long term trials and the used methodology will be able to integrate the long term effects of nutrient availability and soil fertility as factors of economic (and ecological) sustainability of reduced tillage and subsidiary cropping systems.

Subsidiary crop application is essential for no-tillage systems if these are intended to increase sustainability. There is a wide range of environments, where these can be applied, and many possibilities ranging from living mulches to intercalary cover crops. Minimum/no- tillage combined with enhanced use of subsidiary crop and appropriate field technology have a high potential for improving efficiency of the cropping system, reducing resource use and increasing overall sustainability. Making the knowledge available to the public with the Cover Crop and Living Mulch

Toolbox was a major step in supporting farmers when choosing species appropriate in their regions as LM or CC and for encouraging others to contribute more to this important collective effort.

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## 4 Potential impact

The *overall aim* of OSCAR was to **Optimise Subsidiary Crop Application in Rotations** by extending existing knowledge, and improving existing and developing novel cropping systems based on cover crops, catch crops, living mulches and other *subsidiary crops* (SC). It addressed the following main objectives that directly translate into expected impacts:

- Improve understanding and use of subsidiary crop/conservation agriculture systems under a broad range of environmental conditions and interactions with management techniques and farm technology
- To increase the range of subsidiary crop species and make more adapted species/varieties available to fill a niche in crop rotations.
- To develop and make available technical solutions.
- To fill key knowledge gaps on soil ecological impacts.
- To fill key knowledge gaps on the agronomy of subsidiary crop and living mulch based cropping systems with emphasis on managing competitive interactions and perennial weeds.
- To fill key knowledge gaps on the phytopathology in subsidiary crop- and living mulch-based cropping systems with emphasis on risks and solutions.
- To facilitate adoption and improvement of conservation agriculture and subsidiary crop systems throughout Europe by making relevant high-quality information available to target groups.

### Improving understanding and use of subsidiary crop/conservation agriculture systems

Testing of cropping systems under a broad range of environmental conditions available in OSCAR and studying the interactions with management techniques and farm technology indicated that:

- It was known before OSCAR that water availability is a main driver for the possibilities of using subsidiary crops as living or dead mulches. The increasing unpredictability of climatic conditions increases the advantages of using SCs in general, however, because they increase yield stability.
- The conditions under which living mulch (LM) with wheat are possible have been clarified in OSCAR and have been made publically available in deliverables 2.1 and 6.1.
- In temperate regions (Germany and Switzerland) and in the Mediterranean (Italy), growing subterranean clover as a LM results in very limited yield reductions due to LM with pronounced beneficial effects: weed suppression, improved soil fertility, including increased soil N supply, and erosion control. In very dense stands of wheat (with yields > 7 t/ha), however, the clover is highly suppressed.
- White clover can be used as living mulch in regions with colder winters, where subterranean clover cannot be grown preferably undersown in spring.
- Cover crops can and should be used more efficiently for weed control than is currently the case. By using optimal rotations and cover crops, herbicide use can be reduced considerably while improving soil fertility, reducing erosion risk and reducing the need for N fertilization.
- In Organic Farming, the use of highly competitive cover crops is one of the core components of any system with reduced or no soil tillage.
- Regarding the economic feasibility, no general conclusions could be drawn on the favorability of conventional or reduced tillage as well as subsidiary cropping systems, because it seems to be highly dependent on site-specific, pedoclimatic circumstances.

Profit reductions due to lower yields can often be counterbalanced by reduced production costs in reduced tillage systems.

- Overall results suggest that subsidiary crop based systems can reduce the economic risk potential of crop production by stabilized main crop yields, which is especially important in view of climate change.

### **Increasing the range of subsidiary crop species available**

OSCAR characterized a large number of species and genotypes of interest as potential living mulches or cover crops. These include legumes and non-legumes as single species and in mixed species stands. Restrictions in use of synthetic antibiotics in livestock production prompted a search for natural components that may exhibit bacteriostatic properties. Such compounds not only help to maximize animal health and well-being, but may also be potentially useful in controlling emissions of methane and ammonia from animal wastes. Species of interest were also assessed for disease resistance to important pathogens in order to make more adapted species/varieties available to fill a niche in crop rotations:

- Several new *Vicia* and *Lathyrus* species have been identified as subsidiary crops, all of which perform as well or better than current commercial varieties of *Vicia sativa* and *V. villosa*, in terms of biomass, N fixation, seed production and weed suppression.
- The large inter- and intra-specific variability observed in the evaluated accessions in terms of their potential as subsidiary crop and/or forages could be utilized. It will allow for the selection of plant species or varieties fit for specific purposes, such as living mulches, cover crops suited for systems with reduced or without use of herbicides or for optimizing rotations with respect to reduced risks of plant diseases.
- The duration of the growth cycle was identified as an important aspect for success in combination with alternative means for cover crop control, such as the roller crimper.
- The complete database is publically available and has provided an important part of the information for the internet based Cover Crop and Living Mulch Toolbox described below.
- Protocols have been developed for farmers to do their own efficient experimentations and are available.
- The energy levels and contents of proteins and valuable secondary metabolites of in many of the newly identified SCs are remarkably high and promise future additional uses of these SCs as animal feed or production of chemical uses including medicinal products. This has the potential to contribute to the closing of the European protein gap.
- Within potential subsidiary crop species there is a certain amount of variation in susceptibility, warranting research into resistance sources (see also below: phytopathological risks and solutions).

### **To develop and make available technical solutions**

The identification of needs, design, and development of technical solutions was a key component of OSCAR.

- The technology for the application of living mulches and cover crops (either within the main crop, or as part of a rotation) is in principle available in the form of appropriate tillage and sowing machinery which has been connected to the toolbox.
- There is, however, no general solution; machinery and technologies have to be chosen and applied in close relation to soil, climate, and crops.



- Proper and successful use of machinery is highly depending on the skills and experience of the user and cannot be done simply by writing and reading a manual.
- The developments with respect to innovations such as sensors allowing accurate sowing of main crop and combinations of living mulch and crop (in terms of rates, location and depth) are evident. Although not yet commercially available on a large scale, they will be within 5-10 years.
- Reduced, or no-tillage, for seedbed preparation is difficult in situations with heavy and wet soils, and under conditions where large volumes of crop residues are present. These problems can be alleviated in part with rotovating superficially (around 5 cm), which had remarkably positive effects on the decomposition of crop residues. This operation is not limiting the capacity of the machinery since high driving speeds can be applied.
- For sowing into large volumes of cover crops, a combination of chemical and mechanical killing/flattening will give the best results.
- Establishing crops by planting seedlings into a mulch layer is still a challenge, but developments with this type of machinery were successful in Italy. However, the SME involved considers the market not large enough for further development activities.
- The experiences from Brazil (no-till sowing equipment, knife rollers for killing cover crops) were highly useful and relevant for the development of such systems in Europe.

### **Soil ecological impacts of RT and SCs**

OSCAR provides comprehensive insights into the early soil ecological impacts of reduced tillage combined with subsidiary crop applications.

- Subsidiary crops promoted soil microbial biomass and its activity but its functional diversity was not affected.
- The early effects of subsidiary crops on soil biochemical properties depended on climatic zone which affected the initial soil properties of the experimental sites. Soil pH, organic matter content and texture classes, together with climate interact with SC management to establish the soil ecological impact.
- SCs can considerably enhance mycorrhizal abundance outside the growing season and early mycorrhizal colonization of the following main crop. The mycorrhizal contribution to plant P uptake was successfully quantified and can be up to 30 % of total P uptake.
- Subsidiary crops did not affect total organic carbon and nitrogen content of soils in the short-term but affected the labile pool by an increase of the extractable C and N fractions that may represent the easily available nutrient source for soil micro-organisms.
- Growing subsidiary crops did not influence the inorganic nitrogen availability in soil with exception of the Mediterranean site. In the boreal, oceanic and temperate climatic zones nitrate and ammonium contents were similar among all treatments before the second main crop was established. In the Mediterranean site the soil nitrate and ammonium contents varied strongly due to climatic effects from year to year.
- The subsidiary crops interacted with tillage and enhanced early benefits such as better soil aggregation and lower erosion risk.
- It could be shown that, compared to the current use and recommendations concerning subsidiary crop application, erosion control can be remarkably improved by choosing the most appropriate subsidiary crop species such as hairy vetch or subterranean clover, the latter especially if used as living mulch. Improved erosion control is both due to improved ground cover and rooting as to a positive effect on soil aggregate stability.

### **Management of competitive interactions and perennial weeds in SC based systems**

The experiments conducted in OSCAR with respect to the **management of living mulches** addressed optimizing seeding densities, geometrical arrangement of seeds, seeding date as well as the choice of living mulch and main crop varieties. Innovative tools for undercutting, vertical cutting and selective mowing were used to improve **management of perennial weeds**.

- Living mulch based systems generally work best under high main crop seeding densities, and in as uniform patterns as possible of both the main and the subsidiary crop.
- In temperate and southern climates, seeding SC and main crop together is generally an option. It is, however, more difficult to achieve a good balance between the living mulch and the main crop in cooler regions. Either the clover canopy will be strongly suppressed by the main crop or white clover will be too aggressive. Traditional undersowing is the better option in cooler climates.
- Two new prototype implements, one (i) that vertically cuts shallow growing roots or rhizomes of weeds and another one (ii) that cuts the roots or rhizomes horizontally, either shallow or deep, were developed during the project period. Both implements cause minimal disturbance of the soil, without harmful effects on subsidiary crops. The control effects were dependent on weed species and conditions. Promising effects were shown for both implements on couch grass (*Elymus repens*) and perennial sow-thistle (*Sonchus arvensis*) when used instead of traditional stubble cultivation in the autumn, and they reduced the risk of erosion. The horizontal root cutter seems to give the same control effects on creeping thistle (*Cirsium arvense*) as deep ploughing. The two new implements are not yet commercially available, but further development is continuing in a new follow-up project. These implements will greatly reduce the future energy needs in mechanical weed control.

### **To determine phytopathological risks and solutions in SC SC-based cropping systems**

OSCAR assessed diseases in the field, investigated methods for improved soil health management and screened potential SCs for their resistance to important wide host range pathogens of legumes and cereals.

- Foliar diseases were in general very low in the multi-environment experiments and long-term experiments. If at all, Increasing diversity sometimes reduced foliar diseases within the systems, while reduced tillage had no effect.
- Similarly, fungal root diseases and plant-parasitic nematode numbers were also overall moderate with a few exceptions that were directly related to extreme local climatic conditions. Reduced tillage and SCs did not increase these diseases.
- The root and foot rot pathogens were highly diverse among sites as a result of variable pedoclimatic conditions. Field history also played an important role.
- Many, but not all, of the potentially interesting new subsidiary crop species identified in WP3 are susceptible to some of the main pathogens affecting the currently most important grain legume pea (*Pisum sativum*). Within potential subsidiary crop species there is a certain amount of variation in susceptibility, warranting research into resistance sources.
- Certain subsidiary crop species have the capacity to suppress especially plant-parasitic nematodes; much of this knowledge became available from the Brazilian partners.
- There are direct and strong positive effects of soil organisms on the soils ability to suppress disease. However, Deteriorated soil structure (e.g. compaction, water logging) counteracts this suppressiveness suppressive effect in the field.
- There are direct and strong additional positive effects of high value soil organic matter (e.g. composts) on soil structure and soil health and thus, the soils ability to suppress disease.



- Relative abundance of *Fusaria* on wheat residues and on subsidiary crops was very low in the multi-environment experiment in Switzerland. However, different subsidiary crop species host specific fungal communities harboring different *Fusarium* species. Nevertheless, mycotoxin concentration in maize kernels of the multi-environment experiment in Switzerland was very low and did not differ among tillage or subsidiary crop treatments.

### **Facilitation of adoption SC based systems throughout Europe by making relevant high-quality information available to target groups**

The web-based cover crop and living mulch toolbox developed in OSCAR has been highly successful in enhancing public interest in these systems and is helping users to find appropriate solutions for their specific needs.

- The Wikis in several languages have made much information available to practitioners, extensionists and scientists as well.
- The decision support tool helps practitioners to identify subsidiary crops of interest for testing.
- The database underlying the toolbox gives access to all data collected to the interested community of scientists as well as end users and will thus encourage further development of new germplasm for diversification of farming systems.
- In addition to the Toolbox functions, the database will help to avoid duplication of research work.

### **Socio-economic impact**

Reduced tillage (RT) usually implies lower management and energy costs compared to conventional tillage (CT), subsidiary crops and reduced tillage are expected to contribute to ecological services. The economic and risk analyses performed in OSCAR (by using Monte Carlo simulations) were aimed at depicting the range of possible outcomes of management changes thus providing a realistic basis for farmers to estimate the potential benefits and risks of intended changes.

- As is commonly known, in the short term trials (two-year crop rotation) CT was more profitable. Still, certain RT cropping systems are more profitable than CT cropping systems. Furthermore, yields in the Brazilian long term trials were higher with lower management costs in RT cropping systems, leading to greatly improved economics compared to CT systems.
- Depending on yields, energy efficiency in RT systems is not always higher than in CT systems in the short term.
- When comparing subsidiary cropping (SC) systems with their respective *control* systems, SC systems display either higher or lower economic benefits and energy efficiency, very much depending on each OSCAR location with their respective energy input, direct and management costs and yields.
- Risk analysis showed that SC crops decreased production risks in the long term trial in Pisa in Italy. In the short term trials risk distribution can be more favorable for CT than RT systems and vice versa, depending on the site.
- Consideration of long term effects (nutrient availability, soil fertility) could substantially improve economic feasibility of reduced/no tillage and subsidiary cropping systems. Our analyses also indicate that the monetary effects of considering the value of nitrogen for

subsequent crops can have a much greater economic impact than the adaptation of farm size and mechanization to regional agrarian structures.

### **Wider societal implications of the project so far**

The perception of OSCAR in the public has been wide as many newspaper articles and also some TV shows have addressed the topics of OSCAR. Reduced erosion, reduced nutrient leakage, increased C sequestration, and increased provision of flowering plants through increased application of subsidiary crops in agriculture have potential impacts on the society as a whole by:

- Reduced wash-off of soil onto roadways and reduction of dust storms.
- Increased habitat for bees and other beneficial insects resulting in less need for insecticides.
- Increased competition with weeds and consequently reduced need for herbicide inputs.
- Reduction of ground water contamination by nitrates and pesticides and thus costs for water cleaning.
- Potentially a contribution to reduction of greenhouse gas emissions from agriculture.

These impacts will reduce public costs in traffic, health costs, and climate change adaptation costs.

### **Main dissemination activities and exploitation of the results**

Dissemination activities of OSCAR were based on field days, on-farm trials, and workshops; internet-based dissemination via the Toolbox, Facebook, Twitter, and You Tube; publications and Interviews in the popular and specialized media including newspapers, magazines, flyers, TV and the involvement of many students at the respective universities.

- Six on-farm trials were conducted in the UK, Germany and Italy with field days directly on these farms together with the farmers. At least 70 field days with overall more than 3000 participants were held through the course of the project with events in all partner countries.
- The Cover crop and Living Mulch Toolbox ([www.covercrops.eu](http://www.covercrops.eu)) has been accessed by users close to 20 000 times with the Wikis very popular with more than 1800 users and more than half a million views by the end of the project. The decision support tool was evaluated by stakeholders on a scale from 1 (not good) – 5 (excellent) and received a mean score of 4.1 for its usefulness in identifying new potential subsidiary crop species.
- Facebook entries and Wikis are multilingual making them very attractive to users with many likes. Much material has shown up there that was provided by non-members of the OSCAR consortium indicating that it is an active and widely used platform.
- Press releases by OSCAR members have been picked up in many places and interviews and articles were published in local newspapers in the partner countries. Articles in farmer magazines have been very successful in creating interest in the project as the authors were often contacted by farmers after the publication. The manufacturer of the WEcodyn machine, Friedrich Wenz was featured in a widely viewed French-German TV documentary by Arte in 2012 “Planting the future, Organic for nine billion people” that is available on-line in many places (e.g. <http://www.provieh.de/node/11226>). Brazilian TV also made a movie that is available under [http://web3.wzw.tum.de/oscar/wiki/index.php/The\\_OSCAR\\_Project](http://web3.wzw.tum.de/oscar/wiki/index.php/The_OSCAR_Project).
- More than 100 conference contributions and so far 12 articles have been published in the peer reviewed scientific community and many more have been submitted or will be published in the near future as the theses connected to OSCAR are terminated.
- More than 50 student projects, BSc, MSC, and doctoral theses were completed within OSCAR and several more will be terminated within the next 12 months. The authors will

become professionals in agriculture, engineering, breeding, advisory services, NGOs, politics, etc. that have worked with subsidiary crop based systems during their formation contributing to the public knowledge basis needed to bring about change.

## **Considerations for maximizing the potential impacts: Policy implications**

### **Need for long term results**

- Longer term results would improve the validity of the economic evaluation. In order to strengthen the validity of economic statements as decision support for farmers in the EU further work on long term effects of reduced tillage and subsidiary cropping systems, especially on yield and quality, is needed.
- Particular attention should be paid to examining entire multiannual crop rotations to evaluate the economics of multiple yield-influencing parameters (e.g. weed infestation, pathogens, nitrogen household) within well-established cropping systems. There is also a short-term need to provide detailed information and advice about the appropriate methods as affected by pedoclimatic conditions to farmers.
- The cover crop and living mulch toolbox (see WP8), if funded in the future, could become an important building block in supporting further EU efforts in greening.

### **Subsidiary crops**

- Farmers can increase their use of cover crops and thus reduce the use of fertilizers and herbicides. This should be supported.
- There is a need to support and remove obstacles to the introduction of new legume crop species. An example is the lists of admissible legume species for the current “EU greening” programs, which contain only a few species, thus impeding biological diversification.
- The potential contribution of SCs to reduce the protein gap in the EU has not been explored systematically. The same applies to secondary metabolites of high interest for human and animal nutrition and/or medicinal uses. This deserves high attention as here ecological and other societal services can be combined in a most efficient way.
- Also, it should be considered to raise the minimum requirements concerning the use of subsidiary crops (especially legumes) in organic farming (and ideally in all farming systems). Not all organic farms that meet many of the formal requirements of organic farming (IFOAM) are successfully addressing sustainability. Organic farming needs to be able to make a strong claim that it is truly sustainable, and this is not always the case. This is the most important contribution of subsidiary crops, and it is not possible without increase in their use. Some larger, market-orientated organic farms without livestock have rotations with a high proportion of cereals and little grass-clover leys and legumes in the rotation, which could be at least in part compensated by subsidiary crops.

### **Technology**

- Availability of appropriate machinery is not a limiting factor for the implementation of living mulches and cover crops into growing systems; there is a wide choice of equipment on the market.
- However, the use of such machinery requires trained and experienced users and tractor operators, as there is no general or generic solution. Each situation is different, so training and extension is crucial for successful application.

- Quick developments in automation, sensor technology and robotization will assist the farmers in the near future to accurately establish crops without undue strain for the operator. Research in this field should be supported.
- There is a need for the development and use of innovative techniques for weed control in cropping systems based on reduced tillage and subsidiary crops without the use of herbicides. Especially further north, where the growing season is shorter, it is necessary to develop new methods for weed control in spring and autumn. There is also a need for developing suitable coulters for the no-till sowing machine used in different conditions.

### **Ecological services**

The wider use of subsidiary/cover crops has to be supported to improve soil erosion control and to enhance soil microbial biomass and its activity as driving force of nutrient biogeochemical cycle. There has been a general loss of soil organic matter increasing system susceptibility to disease. The work done in OSCAR and also published internationally by other groups over the past few years points to the potential of severe soil borne disease outbreaks on many different plants in systems low in organic matter. This is due to the fact that suppression of many soil borne fungal pathogens depends on high soil organic matter and microbial activity in soils. Reduced tillage combined with the use of cover crops or living mulches clearly contributes to an increase in soil organic matter (see WP5) and improved soil structure and thus to the soils potential to suppress pathogens. Besides, the use of subsidiary crops can reduce the need for herbicides especially when combined with the appropriately timed technology (See WP4).

- Applied research and (at least tentative) introduction into all types of agriculture of living mulches or species mixtures in order to preserve soil quality, as main principle of sustainable agriculture needs to be supported. There is also a need for work on breeding, improvement, and introduction of new subsidiary crop species in order to increase their frequency in the rotations (since a direct relation can be found between above and below ground biodiversity).
- Encourage and enable the choice of cover crop species based on environmental conditions since their performance on soil quality improvement is strongly related to climate. For this the toolbox and the decision support tool should be kept active and growing beyond OSCAR. This applies especially to the use of legumes as cover crops and living mulches, which have shown manifold beneficial effects on the soil, weed control and nutrient supply (as well as other ecosystem services such as pollinators). This relates also to the comment above on the lists of admissible legume species for the current “EU greening” programs, which contain only a few species, thus impeding biological diversification.
- Support further applied research for machinery, which is often a reason for non-application of new cropping methods in agriculture.
- As mentioned above, consider raising the minimum requirements concerning the use of subsidiary crops (especially legumes) in organic farming to enhance the sustainability requirements of organic farming (IFOAM). Here, some of the legislative rules implemented in southern Brazil (Parana) could be of interest for inspiration.
- In order to strengthen the validity of economic statements as decision support for farmers in the EU further investigations on long term effects of reduced tillage and subsidiary cropping systems, especially on yield and quality effects, are needed. Particular attention should be paid to examining entire multiannual crop rotations to also economically evaluate the multiple yield-influencing parameters (e.g. weed infestation, pathogens, nitrogen household) within well-established cropping systems and to attribute value to ecological services.

## Concluding remarks

In conclusion, OSCAR has made a significant impact in the field of subsidiary crop applications by (i) systematically providing information on the interactions of reduced tillage and SC applications with pedo-climatic conditions including main soil ecological interactions, (ii) testing and providing innovative agronomic and technology solutions for managing SCs and weeds, (iii) identifying and characterizing new germplasm for usefulness including disease resistances, protein contents, contents of valuable secondary metabolites, (iv) developing methods for disease management, and (v) making this knowledge widely accessible through the Living mulch and Cover Crop Toolbox ([www.covercrops.eu](http://www.covercrops.eu)). Joining forces with Brazilian researchers involved in one of the longest research programs on reduced tillage and cover crop use has been highly valuable and produced many synergies.

There is a need to actively support the use of subsidiary crops and the breeding and selection for new subsidiary crops and the combinability of these with main crops to increase overall system biodiversity and resilience. The overall benefits of such practices go beyond agriculture, as this will reduce dependence on external inputs, soil erosion, and problems with surface and ground water quality, which are clearly benefits to society. Specific recommendations are:

- The use of subsidiary and cover crops should be encouraged as their use can result in a reduction in fertilizer and herbicide use as well as enhance soil microbial biomass and improve soil erosion control.
- Remove obstacles to the introduction of new legume crop species through expanding the lists of admissible legume species for the current “EU greening” programs.
- Support breeding of cover crop species with focus on the selection for disease resistance and for combining ability of main crops with living mulches.
- Support training for farmers. The use of machinery requires trained and experienced operators, as there is no general or generic solution. So training and extension is crucial for successful application.
- Make information easily available to farmers which could be addressed by maintenance and further development of the toolbox.
- Research in the field automation, sensor technology and robotization should be supported.
- Raise the minimum requirements concerning the use of subsidiary crops (especially legumes) in organic farming and conventional farming.