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By David Navarro-Miró, José M. Blanco-Moreno, Corrado Ciaccia, Elena Testani, Ileana Iocola, Laura Depalo, Giovanni Burgio, Hanne Lakkenborg Kristensen, Margita Hefner, Kalvi Tamm, Ingrid Bender, Alessandro Persiani, Mariangela Diacono, Francesco Montemurro, Koen Willekens, Hélène Védie, Martina Bavec, Martina Robačer, Donatienne Arlotti, Pauline Deltour, Stefaan De Neve, Mesfin Tsegaye Gebremikael, Lourdes Chamorro, Berta Caballero-López, Alejandro Pérez-Ferrer, Stefano Canali, Francesc Xavier Sans

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1	The concurrent assessment of agronomic, ecological, and environmental variables
2	enables better choice of agroecological service crop termination management
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# 48 Abstract

49 1. Although organic farming was originally promoted as an alternative farming system to address 50 agronomic, environmental, and ecological issues, its conventionalisation has led to an 51 intensification and specialisation of production. In light of this, several studies have questioned the 52 environmental benefits of organic farming as well as its agronomic viability. Thus, there is a need 53 to improve organic vegetable systems to reduce their environmental impact without affecting their 54 productivity. To tackle this challenge, European farmers and researchers have recently started to 55 focus on agroecological service crops (ASCs). However, few studies have simultaneously evaluated 56 the agronomic, environmental, and ecological aspects of ASC management under different 57 European pedo-climatic conditions.

- 58 2. We evaluated effects of the ASC management strategies: no-till roller crimping (NT-RC) and green
  59 manuring (T-GM) on cropping system performance using agronomic, environmental, and
  60 ecological indicators, to exemplify the need for multidimensional analysis to understand
  61 management implications for addressing environmental and agronomic challenges. We combined
  62 the results from eleven organic vegetable field trials conducted in seven European countries over a
  63 period of two years to test for general trends.
- 64 3. Our results provide solid evidence that NT-RC management across different pedo-climatic
  65 conditions in Europe enhances the activity density of ground and rove beetles, and improves both
  66 the potential energy recycling within the system and weed control. However, in NT-RC plots lower
  67 cash crop yield and quality, energetic efficiency of production, and activity density of spiders was
  68 observed compared to T-GM.
- 4. Synthesis and applications: Multidimensional analyses using agronomic, environmental, and ecological indicators are required to understand the implications of agricultural management in agroecosystem functioning. Introducing agroecological service crops combined with the use of no-till roller crimping is a promising strategy for improving agronomic performance (e.g., fewer weeds) and reducing environmental (e.g., increasing the potentially recyclable energy), and ecological (e.g., enhancing the activity density of beneficial taxa such as ground and rove beetles) impacts. However,
- 75 our study also indicates a need for agronomic and environmental improvements while promoting a
- wider acceptance of this strategy.

# 77 Key words

- 78 Energetic efficiency; ground beetles; potentially recyclable energy; rove beetles; spiders; weed control;
- 79 yield

# 80 1. Introduction

- 81
- 82 Agriculture provides multiple ecosystem services that are indispensable for human welfare and these
- 83 depend on a network of supporting (e.g., soil fertility and nutrient cycling) and regulating (e.g., pest and
- 84 weed control) services. However, the management of cropping systems can also generate disservices

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that reduce productivity (e.g., pest damage), generate environmental issues (e.g., nutrient leaching), and
affect both the maintenance and functioning of ecosystems and human well-being (Power, 2010; Zhang,
Ricketts, Kremen, Carney, & Swinton, 2007).
In Europe, 1.9 % of arable land (2.2 million ha) is devoted to vegetable crops and produces
approximately 65 million tonnes of fresh vegetables (De Cicco, 2016; EUROSTAT, 2019). Vegetables
are the crops that need the highest energy input (Elsoragaby, Yahya, Mahadi, Nawi, & Mairghany, 2019)
and, to ensure yields, vegetable production currently requires the greatest agrochemical input (i.e.,

of these crops has caused environmental problems, including the notable consumption of non-renewable
resources and nutrient leaching (Min, Zhang, & Shi, 2012; Torrellas et al., 2012) as well as health
concerns derived from the presence of pesticide residues (González-Rodríguez, Rial-Otero, CanchoGrande, & Simal-Gándara, 2008).

fertilisers and pesticides) and the highest irrigation rates of all arable systems. Intensive management

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Organic farming was originally promoted as a holistic farming system aimed at improving soil health,
and environmental and social aspects of agricultural production (Seufert, Ramankutty, & Mayerhofer,
2017). In recent decades, its conventionalisation has led to the intensification and specialisation of
organic production (Buck, Getz, & Guthman, 1997; Darnhofer, Lindenthal, Bartel-Kratochvil, &
Zollitsch, 2010), and several studies have questioned the environmental benefits and agronomic
viability of organic farming (Seufert et al., 2017; Trewavas, 2001, 2004; Tuomisto, Hodge, Riordan, &
Macdonald, 2012).

104 There are also agronomic limitations to the widespread implementation of organic farming, of which 105 weed management is identified by organic farmers as one of the main constraints on organic arable 106 vegetable production (Turner, Davies, Moore, Grundy, & Mead, 2007). For example, the dependence 107 on frequent soil tillage for controlling weeds negatively affects the sustainability of soil management in 108 organic systems (Trewavas, 2001, 2004). This is because tillage is very energy-consuming and increases 109 fossil fuel consumption (Alluvione, Moretti, Sacco, & Grignani, 2011). In addition, tillage has a direct 110 impact on soil organisms (i.e., by directly killing or injuring them) and their habitat, and modifies inter-111 specific relationships (Roger-Estrade, Anger, Bertrand, & Richard, 2010). In particular, ground and 112 rove beetles are known to be sensitive to soil disturbance (Pretorius et al., 2018; Rivers, Mullen, Wallace, 113 & Barbercheck, 2017; Tamburini, De Simone, Sigura, Boscutti, & Marini, 2016). Moreover, the 114 negative impact of tillage on certain groups of soil-dwelling predatory invertebrates also affects the 115 biological pest-control potential of this cropping system (Tamburini et al., 2016). Finally, intensive 116 tillage causes changes in the biological quality of the soil and, for example, affects the activity of 117 enzymes (e.g., beta-glucosidase) that play important roles in organic matter degradation (Ekenler & 118 Tabatabai, 2003).

119 Another important constraint is related to the gap in crop yield between organic and conventional farming systems (Ponisio et al., 2015). Some studies argue that organic farming is less efficient as it 120 121 requires more land to produce the same amount of food as conventional farming, and that more fossil 122 fuel is required for weed control (Trewavas, 2001, 2004). Additionally, under organic farming, the 123 adoption of less intensive tillage management has been shown to potentially reduce the cash crop yield 124 and fruit quality (i.e., the marketable parameters) (Ciaccia, Montemurro, et al., 2015; Diacono, Persiani, 125 Fiore, Montemurro, & Canali, 2017). Fertilisation strategies based on the application of animal or green 126 manure, as well as the recycling of energy and nutrients within the cropping system, are also argued to 127 have potentially negative impacts on the environment (Trewavas, 2001, 2004). On the one hand, the 128 process of manure decomposition and nutrient release from animal or green manure is not always well 129 synchronised with the cash crop uptake. After the cash crop cycle, the manure remaining in the soil 130 continues to decompose and release nutrients that can lead to nitrate leaching and the eutrophication of natural water bodies (Trewavas, 2001). On the other hand, Trewavas (2004) highlighted the fact that
recycling energy and nutrients within the cropping system cannot compensate for the absorption of
nutrients by the cash crop. Therefore, this type of management can lead to a progressive depletion of
these nutrients in the soil.

135 To overcome some of these constraints, organic vegetable cropping systems need to be re-evaluated 136 and their impacts addressed from an agronomic, environmental, and ecological perspective. The 137 introduction of agroecological service crops (ASCs) (e.g., catch crops, cover crops, and complementary 138 crops) (Canali, Diacono, Campanelli, & Montemurro, 2015) in crop rotations is a widely recognised 139 strategy for improving the environmental performance of cropping systems (Silva, Moore, Silva, & 140 Moore, 2017; Wezel et al., 2014). Nevertheless, several authors have concluded that the environmental 141 and agronomic performance of ASCs depends on the management strategy used to terminate them 142 (Canali et al., 2013; Ciaccia et al., 2016; Navarro-Miró, Blanco-Moreno, et al., 2019; Navarro-Miró, 143 Iocola, et al., 2019).

144 Traditionally, European organic farmers have managed ASCs as green manure (T-GM) by chopping up 145 and incorporating plant material into the soil by tillage (Peigné et al., 2016). However, as stated above, 146 tillage can negatively affect the soil system. In recent years, therefore, the use of no-till roller crimping 147 (NT-RC) for ASC management has attracted the interest of European farmers and researchers 148 (Casagrande et al., 2016; Vincent-Caboud, Peigné, Casagrande, & Silva, 2017) because it can improve 149 weed management and reduce dependence on tillage in organic farming. The roller-crimper flattens the 150 ASC, creating a dense layer of plant residue on the soil surface (i.e., mulch) without soil disturbance. 151 The use of NT-RC for ASC management originated in Brazil (Kornecki, Price, Raper, & Arriaga, 2009), 152 and this approach has been studied and developed mainly in Latin America, Canada, and the USA 153 (Altieri et al., 2011; Carr, Gramig, & Liebig, 2013; Delate, Cwach, & Chase, 2012; Shirtliffe & Johnson,

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154 2012). The few studies performed in European organic vegetable systems have concluded that NT-RC 155 reduces weed abundance dramatically and requires less fossil fuel than the T-GM approach (Canali et 156 al., 2013; Ciaccia, Testani, et al., 2015; Diacono et al., 2017). Nevertheless, both positive and negative 157 effects have been observed on cash crop yields when NT-RC is implemented under Mediterranean 158 conditions (Canali et al., 2013; Ciaccia et al., 2016; Diacono et al., 2017). In addition, few studies have 159 examined the impact of cover crop termination on beneficial soil fauna (Depalo et al., 2020; Magagnoli 160 et al., 2018), root growth, and soil nitrogen (Hefner, Canali, et al., 2020; Hefner, Gebremikael, et al., 161 2020).

162 Most studies that have analysed NT-RC have focused on agronomic aspects and, to a much lesser extent, 163 on environmental performance. To our knowledge, no studies have used a multidimensional approach 164 to evaluate different agronomic, environmental, and ecological aspects simultaneously. Furthermore, 165 most studies have been conducted under the particular conditions of specific experimental sites 166 (including crops, weather, and soil), which may have influenced the findings. Given that agroecological 167 patterns can be affected by the nature of the receiving environment, validation of practices must take 168 into account this potential variability. The only studies to have analysed the effect of NT-RC on energy 169 flows and weed control across Europe are, respectively, Navarro-Miró, Iocola, et al. (2019) and 170 Navarro-Miró, Blanco-Moreno, et al. (2019).

In this study, we analysed effects of the ASC management strategies (NT-RC vs. T-GM) on organic vegetable cropping system performance by means of agronomic, environmental, and ecological indicators, in different vegetable crops, soils and climatic conditions across Europe. We compared NT-RC and T-GM using a system comparison approach to exemplify the need for multidimensional analysis to address some of the most frequent criticisms and constraints as mentioned above. We also aimed to show the importance of an appraisal of the environmental and ecological implications—as well as the agronomic benefits to the agroecosystem—under different crop, soil, and climatic conditions to evaluate
the pros and cons of the different management systems before promoting them to organic vegetable
farmers, advisors, and policymakers. To this end, we combined results obtained over a two year period
from eleven organic vegetable field trials located in seven European countries as part of the SoilVeg
project (ERA-Net CORE Organic Plus).

182

## 183 2. Material and methods

## 184 2.1. Locations and field trials

We combined results from 11 organic arable vegetable field trials located in Belgium (BE), Denmark
(DK), Estonia (EE), France (FR), Italy (IT), Slovenia (SI), and Spain (ES). In BE, three different trials
were set up across the country (BE-ILVO, BE-INAGRO, and BE-CRA-W). These vegetable production
trials were located in different climatic zones (Metzger, Bunce, Jongman, Mücher, & Watkins, 2005)
and had different soil textures (Table 1).

190 Two parallel field experiment types were carried out during two crop cycles as part of the SoilVeg 191 project. Field experiment type A (FtA) was established at all trial locations (BE-ILVO, BE-INAGRO, 192 BE-CRA-W, DK, EE, ES, FR, IT, SI) and involved the introduction of cold-rainy season ASCs into the 193 crop rotation, followed by a spring-summer cash crop. The first FtA cycle took place during 2015 and 194 2016 and the second, during 2016 and 2017. Field experiment type B (FtB) was performed only at the 195 IT and ES locations where the Mediterranean climatic conditions enabled introduction of the ASCs in 196 the warm-dry season (i.e., summer) with irrigation, followed by the transplantation of an autumn-winter 197 cash crop. The first FtB cycle took place during 2014 and 2015 and the second, during 2015 and 2016. 198 The comparison between ASC management strategies (NT-RC vs. T-GM) was carried out within each

- trial for both experiment types. In total, results from twenty-two original datasets were analysed (i.e.,
- from 11 field experiments carried out over two years) (Table 1).

### 201 2.2. Trial management

202 All field trials were newly established. Both experiment types were repeated in the same plots during 203 both years in ES and BE-ILVO, whereas in the other trial locations, new plots were established in 204 adjacent areas of the same experimental field following a planned rotational design for the second year 205 of experimentation. Notwithstanding different weather conditions, soil textures, ASC compositions, and 206 experimental designs (Table 1), a comparison between the two ASC management strategies (NT-RC 207 vs. T-GM) could be made for all trials. The NT-RC strategy involved: (1) ASC flattening by several 208 roller crimper passages (2-4) to obtain a mulch of plant residue, and (2) the creation of a narrow 209 transplanting furrow without disturbing the surrounding mulch using a slower in-line tiller. The T-GM 210 strategy involved: (1) ASC mowing and/or chopping, (2) incorporation of the ASC pieces into the soil 211 by tillage, and (3) preparation of the seedbed. Further information about the experimental design and 212 agronomic management in each trial is provided in Appendix S1 in Supporting Information.

213

#### 214 **2.3.** Cropping system performance indicators

We used a set of ecological, environmental, and agronomic indicators with a system comparison approach to compare the performance of NT-RC and T-GM. In addition to a set of common indicators evaluated in all experiments, we selected a number of tailored indicators which were used according to the site-specific aims and conditions of the different experiments.

219

220 2.3.1. Ecological and environmental indicators

221 We investigated the effects of ASC management on the soil system by analysing its impact on soil 222 arthropod fauna and soil enzyme activity. We followed the concept of ecological indicators sensu 223 McGeoch (1998) because the functions represented by these indicators are of significance to agriculture 224 (Niemelä, 2000). The impact of the ASC management strategies on the soil fauna was assessed by 225 evaluating the activity density of ground (Carabidae) and rove (Staphylinidae) beetles and spiders 226 (Araneae). These soil taxa have been shown to be sensitive to agricultural input and practices, including 227 tillage, and are often used to typify the effect of agricultural practices on organisms living on the soil 228 surface (Pretorius et al., 2018; Rivers et al., 2017). The activity densities (AD) of the Carabidae, 229 Staphylinidae and Araneae were assessed using pit-fall traps. Specific details of pit-fall trapping, 230 number and duration of sampling periods in each trail are provided in Appendix S2. In each trial, soil 231 arthropod AD was calculated as the mean of the abundance of each taxonomic group in all samples 232 divided by the number of traps and the number of days that traps were operative. The AD was 233 normalised to seven days:

 $234 \quad \text{AD} = \frac{n}{T} \cdot \frac{7}{d}$ 

where *n* is the total abundance of each taxon, *T* is the number of traps, and *d* is the number of days that traps were operative.

The effect of the ASC management strategy on soil quality was assessed using beta-glucosidase enzyme
activity. This enzyme has known sensitivity to soil tillage, irrespective of pedo-climatic conditions, and
can, therefore, provide rapid information regarding changes in soil properties (Ekenler & Tabatabai,
2003; Knight & Dick, 2004). In BE-INAGRO and DK beta-glucosidase was assessed using the method
described in Alef and Nannipieri (1995), while in IT was determined by the procedure described by
Fornasier and Margon (2007).

243 In the FtA trials, soil mineral nitrogen was measured by colorimetry at cash crop harvest as an indicator 244 of the nitrogen leaching potential (N leaching). According to Hutchings and Kristensen (1995), it can be 245 assumed that the remaining soil mineral nitrogen at the end of the growing season, which coincides 246 with the beginning of the leaching season, will be leached during the winter. The potential recycling of 247 material and energy within the cropping system was calculated using the concept of potentially 248 recyclable energy (PRE) as an output of the cropping system in the energy-use efficiency indicator 249 (PRE-EUE) (Navarro-Miró, Iocola, et al., 2019). The PRE incorporates all the energy that can 250 potentially be recycled within a cropping system, including the energy contained in ASCs, weeds, and 251 cash crop residues (comprising discarded yield and other plant matter). The PRE-EUE indicator was 252 calculated dividing the PRE by the total energy inputs of the cropping system (human labour, diesel 253 consumption, electricity, water for irrigation, ASC seeds, cash crop plantlets, organic fertilizers and 254 organic soil amendments, crop protection inputs, and the machinery-embodied energy fraction 255 estimated on the basis of the machinery weight and economic life). This indicator provides insight into 256 the capacity of the cropping system to transform inputs into potentially recyclable energy. A description 257 of the agronomic operations carried out in the evaluated trials, and the energy equivalents of the inputs 258 and outputs used is provided in Navarro-Miró, Iocola, et al. (2019).

Further details of beta-glucosidase enzyme activity determination and the assessment of soil mineralnitrogen at harvest of the cash crop are provided in Appendix S2.

261

262 2.3.2. Agronomic indicators

We evaluated the effects of the ASC management strategies on two indicators: the cash crop marketable yield, and the cash crop quality. The cash crop marketable yield indicator was assessed using the dry biomass of the marketable cash crop yield, whereas the cash crop quality indicator included different measurements of the cash crop marketable parameters, specific to each crop (cabbages - head diameter; pepper - fruit length; butternut squash - fruit weight; tomato - fruit total soluble solids with
refractometric index, °Brix; cauliflower - marketable head dry matter weight), as indicated in Appendix
S2.

270 The energy efficiency of the marketable production was determined by the energy-use efficiency 271 indicator (M-EUE) (Barut, Ertekin, & Karaagac, 2011). For M-EUE, we considered the marketable 272 yield of the cash crop as the output and was divided by the total energy inputs of the cropping system. 273 Further details of the agronomic operations and the energy equivalent calculations can be found in 274 Navarro-Miró, Iocola, et al. (2019). Weed control was analysed by determining weed density 275 (individuals m<sup>-2</sup>). To account for all the potential competition effects on the cash crop, we included the 276 number of germinated and regrown weed plants and ASC species at an early stage of cash crop growth, 277 before the first weeding operation. Specific details of weed sampling (i.e., the number of samples per 278 plot) and timing are provided in Navarro-Miró, Blanco-Moreno, et al. (2019).

279

#### 280 **2.4.** Statistical analysis

Each trial was conducted under its own particular pedo-climatic conditions and experimental design.
Thus, instead of pooling the raw data from all the different trials, we fitted a statistical model for each
trial and indicator. We used a meta-analytic approach to combine the *P*-values and assess the effect of
the ASC management strategies on each indicator for all the trials. This approach is known to be almost
as powerful as approaches based on data combination (Zaykin, 2011).
Statistical models for each partner were fitted according to the experimental variables evaluated and the

experimental layout, and included all the experimental variables evaluated in each trial in order to rule

288 out their effect on the dependent variable. The levels of the experimental variables included in each

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289 model are presented in Table 1. Total dry biomass (ASCs and weeds) was used as a covariate, calculated 290 by pooling the different ASCs included in each trial and the weeds present prior to ASC termination. 291 For the BE-ILVO, BE-INAGRO, BE-CRA-W, DK, EE, FR, IT, and SI trials, we used linear mixed-292 effects models and defined random effects according to the specific experimental layout of each trial, 293 as detailed in Table 1. However, for ES, given that the experimental layout was influenced by the need 294 to facilitate the movement of machinery between plots, we introduced spatial correlation structures in 295 the generalised linear models to account for the lack of independence between samples (Pinheiro & 296 Bates, 2000). Thus, we established the best model for each dependent variable comparing different 297 classes of spatial correlation structures as well as a model with no spatial correlation structure using 298 likelihood ratio tests and Akaike's information criterion. Data were transformed when necessary to 299 ensure the normality and homoscedasticity of the residuals. All statistical analyses were performed with 300 R software (R Core Team, 2018). For linear mixed-effects models, we used the lme function of the R 301 nlme package (Pinheiro, Bates, DebRoy, Sarkar, & R Core Team, 2017), except for BE-CRA-W and 302 IT-N leaching and IT-beta-glucosidase enzyme activity models, for which we used the lmer function 303 of the R lme4 package (Bates, Mächler, Bolker, & Walker, 2015). For the IT trial, the AD of ground 304 and rove beetles and spiders was analysed using the glmer.nb function of the lme4 package (Bates 305 et al., 2015). For the ES trial, we fitted the models with spatial correlation structures using the gls 306 function. Then, the statistical significance of the effect of the management strategy on a specific 307 indicator for all the trials was analysed using the weighted Z-test, which is essentially a weighted version 308 of Stouffer's method, as in Zaykin (2011):

309  $p_Z = 1 - \Phi \left( \frac{\sum_{i=1}^k w_i Z_i}{\sqrt{\sum_{i=1}^k w_i^2}} \right)$ 

where  $Z_i = \Phi^{-1}(1-p_i)$ ; pi is the *P*-value from the i-th study out of a total of k studies;  $w_i$  is the weight 310 selected for the study; and  $\Phi$  and  $\Phi^{-1}$  are are the standard normal cumulative distribution function 311 312 and its inverse, respectively. For this study, we weighted Zi using the standardised effect size:  $w_i = \frac{|\mu_i|}{SE_i}$ 313 where  $\mu_i$  is the coefficient estimate, and SE<sub>i</sub> is its standard error. To test for the same alternative 314 315 hypothesis, individual *P*-values were converted to one-sided values before combining as follows:  $p_{one-sided} = \begin{cases} \frac{p_{two-sided}}{2}, & \text{if the direction of the effect coincides with the alternative hypothesis} \\ 1 - \frac{p_{two-sided}}{2}, & \text{otherwise.} \end{cases}$ 316 317 Independence between *P*-values is required for the weighted Z-test. Thus, we analysed the data from 318 the two consecutive years of each trial simultaneously and obtained the average effect of the termination 319 strategy in each trial after taking into account the effect of the year.

# 320 **3. Results**

321

# 322 **3.1.** Environmental and ecological indicators

The statistical analysis showed that the ASC management strategy significantly affected soil arthropod
AD and PRE-EUE (Figure 1), whereas it had no significant effect on the beta glucosidase indicators or
N-leaching across the trials, except for the BE-CRA-W trial where the N leaching potential was
significantly affected (Table 2).
According to the weighted Stouffer's test, the Carabidae AD was significantly higher under NT-RC
compared to T-GM across the trials (Figure 1) except in SI-FtA under NT-RC where a significantly

- 329 lower AD was observed (Table 2). The weighted Stouffer's test showed that Staphylinidae AD was also
- 330 significantly higher under NT-RC compared to T-GM (Figure 1). We observed a significantly higher

Staphylinidae AD under NT-RC in IT-FtA and IT-FtB whereas in BE-ILVO-FtA and SI-FtA, the
Staphylinidae AD was significantly lower (Table 2). Spider AD was lower under NT-RC than T-GM
across the trials (Figure 1), but only significantly so in two out of the five evaluated trials (Table 2).
The energy recycling efficiency of the ASC management strategies (evaluated using the PRE-EUE
indicator) was significantly higher across trials under NT-RC compared to T-GM (Figure 1). The PREEUE was significantly higher under NT-RC in four out of eight trials, and was significantly lower only
in IT-FtB (Table 2).

338 The ranges (i.e., maximum and minimum) of the environmental and ecological indicators for each trial339 are presented in Appendix S3.

#### 340 **3.2.** Agronomic indicators

341 All agronomic performance indicators were significantly affected by the ASC management strategy 342 (Table 3). Weed density under NT-RC was lower than under T-GM (Figure 1) and declined significantly 343 in seven out of nine trials (Table 3). According to the weighted Stouffer's test, both yield descriptors 344 (i.e., cash crop marketable yield and quality) were lower under NT-RC compared to T-GM (Figure 1). 345 Similarly, the energy-use efficiency of the ASC management strategies evaluated using marketable 346 yield as the output of the cropping system was lower under NT-RC compared to T GM (Figure 1), and 347 was significantly lower in four out of eight trials. However, energy use efficiency under NT-RC was 348 significantly higher in ES-FtA and IT-FtA (Table 3).

349 The ranges (i.e., maximum and minimum) of the agronomic indicators for each trial are presented in350 Appendix S3.

# 351 **4. Discussion**

352 The system comparison approach between NT-RC and T-GM shows the importance of 353 multidimensional analysis for evaluating the advantages and disadvantages of agricultural practices 354 from an environmental, ecological, and agronomic perspective before they can be promoted by advisors 355 and policymakers, and implemented by organic vegetable farmers. We acknowledge that our study 356 reports only on the overall trend of the differences between management systems. Although we cannot 357 make inference on the distribution or the magnitude of the effects on the different indicators beyond the 358 study locations without further research, we provide a strong support, derived from several experiments, 359 for the trends presented. Our results show that each of the ASC management strategies affected the 360 performance of the agronomic, environmental, and ecological indicators differently. Thus, the 361 multidimensional analysis showed that none of the ASC management strategies analysed can address 362 all the most frequent limitations and criticisms of organic farming.

The overall results indicate that, in spite of some differences between trials, NT-RC enhanced weed control in the early growing season, and the AD of ground and rove beetles as well as the potential recycling of energy within the system when compared to T-GM. However, compared to T-GM, NT-RC lowered cash crop yield and quality, the energetic efficiency of production, and the AD of spiders in the vegetable crops and under the different soil and climatic conditions in the representative European countries.

The consistent effectiveness of NT-RC on reducing weed density across countries validates this approach as an effective strategy for European organic farmers to manage weeds during the early stages of vegetable growth. It is worth noting that other studies on the reduction of tillage intensity in organic farming analysed the effect of both ASC management strategies on weed density, weed species richness, and community composition (Navarro-Miró, Blanco-Moreno, et al., 2019). Implementation of NT-RC may lead to a decrease in the dependence on tillage for managing weeds, which in turn may result in 375 less soil disturbance in organic vegetable systems. Moreover, the AD of ground and rove beetles were 376 higher under NT-RC plots, which are generally sensitive to soil disturbance (Pretorius et al., 2018; 377 Rivers et al., 2017; Tamburini et al., 2016). Our results agree with previous studies regarding the effects 378 of ASC termination on soil functional diversity (Depalo et al., 2020; Magagnoli et al., 2018). The NT-379 RC strategy has been shown to reduce the direct impact of tillage (for ASC incorporation and weeding 380 operations) on organisms living in the upper soil layers (Roger-Estrade et al., 2010; Sommaggio, Peretti, 381 & Burgio, 2018) and to create favourable conditions (i.e., physical refuges and prey provision) for these 382 groups during the cash crop cycle (Roger-Estrade et al., 2010; Sunderland & Samu, 2000). These soil-383 dwelling taxa play an important role in agroecosystem functioning, as they include pest and weed-seed 384 predators and detritivores. For these reasons, their conservation and promotion may enhance the 385 provision of ecosystem services (Pretorius et al., 2018).

In our study, spider AD was lower under NT-RC compared to T-GM across trials. This finding contradicts a growing body of work indicating the positive effects on spider abundance of straw mulch (Sunderland & Samu, 2000), and of conservation tillage (Tamburini et al., 2016). The lack of a clear pattern between ASC termination strategy and spider populations calls for further studies to improve knowledge of how flattened mulch may affect macrofauna based on body size, movement, behaviour, guild, and dispersal methods (Baatrup, Rasmussen, & Toft, 2018; Cardoso, Pekár, Jocqué, & Coddington, 2011; Jiménez-Valverde, Baselga, Melic, & Txasko, 2010).

393 Our NT-RC findings do not counter some of the main criticisms of this termination strategy regarding 394 the yield and production efficiency of organic systems. Our results indicate that there is a consistent 395 pattern of decreasing vegetable cash crop yield and marketable fruit quality under certain pedo-climatic 396 conditions and crops. The reduction of the cash crop yield is one of the main drawbacks of no-till 397 management, specifically when organic fertilisers are applied (Pittelkow et al., 2015). Overall, greater

398 variability and lower cash crop yields are one of the factors hindering a more widespread adoption of 399 no-till practices by European organic farmers (Casagrande et al., 2016; Vincent-Caboud et al., 2017). 400 The negative effect of NT-RC on crop yield was related to limited N availability in the DK trial (Hefner, 401 Gebremikael, et al., 2020). Similarly, other published literature links the yield gap and fall in marketable 402 quality under NT-RC in organic vegetable systems to N shortages during cash crop development 403 (Ciaccia, Montemurro, et al., 2015; Diacono, Persiani, Canali, & Montemurro, 2018; Diacono et al., 404 2017). Therefore, this line of evidence points to the need for improvement of fertilisation strategies to 405 overcome this constraint in combination with the species chosen as the agroecological service crop as 406 shown in the DK trial (Hefner, Canali, et al., 2020). Additionally, NT-RC was less efficient than T-GM 407 in transforming inputs into marketable outputs. A reduction in M-EUE can be related to higher cash 408 crop yields and/or lower energy input consumption (Mohammadi & Omid, 2010). In our study, the 409 greater input consumption required by T-GM for tillage and weeding operations (Canali et al., 2013; 410 Diacono et al., 2018) could be compensated by the higher yield and better quality observed with this 411 management strategy.

412 Implementation of NT-RC improved the environmental performance in terms of the energy that could 413 potentially be recycled within the cropping system. Flattening the ASCs and avoiding tilling prior to 414 cash crop transplantation has been shown to increase the efficiency of the cropping system in terms of 415 the potentially recyclable energy generated per unit of input invested (Navarro-Miró, Iocola, et al., 416 2019). Although future energy and nutrient input savings might result in the long term due to the higher 417 retention of energy within the agroecosystem, the higher PRE observed in NT-RC plots was mainly 418 caused by a higher non-marketable yield rate, which is not agronomically desirable. Therefore, more 419 research is required to analyse whether the likely input savings would compensate for the higher 420 proportion of non-marketable yield observed under NT-RC in the long term. Regarding beta421 glucosidase activity, no clear conclusion could be drawn in the short term from the findings of the 422 present study. Similarly, the leaching of mineral N as a potential environmental indicator was only 423 significantly affected by the ASC management strategies in one of five trials, and there was no common 424 significant pattern across trials. 425 In this study, the response of agroecosystem functioning to the different ASC management strategies 426 was evaluated immediately after their implementation. Similarly to what is found in other agricultural 427 systems (Cooper, Baranski, et al., 2016) the benefits from all forms of reduced and conservation tillage 428 are cumulative and accrue over many years, so a single year of observations is likely to underestimate 429 not only the benefits of these particular approaches, but also the broader ecological consequences. 430 Therefore, longer-term studies are required to improve our understanding of the processes associated 431 with organic NT-RC, and to evaluate whether this strategy is effective as a continuous long-term 432 management approach.

# 433 **5.** Conclusions

434 In this study, we evaluated the consequences of a change in the management of organic vegetable 435 production, from an agronomic, environmental, and ecological perspective. This study provides the first 436 evidence that NT-RC alleviates some limitations of organic systems, mainly ecological and to lesser 437 extent environmental and agronomic indicators in different vegetable crops and soils, and under different climatic conditions in Europe. However, compared to T-GM, NT-RC affects negatively some 438 439 ecological and many agronomic indicators. Therefore, our results highlight the need to simultaneously 440 evaluate different agronomic, environmental, and ecological aspects as a means of providing a clearer 441 overview of the effect of ASC management strategies on agroecosystem functioning. Further research 442 is thus required to determine how to reduce the yield gap under NT-RC via the use of new fertilisation

443 strategies during cash crop development or in specific vegetable breeding programs. Additionally,
444 studies performing economic analyses should be run to assess whether the costs associated with NT445 RC compensate the reduction in cash crop yield and quality. Therefore, it is clear that for the promotion
446 of any agricultural system it is necessary to undertake a thorough analysis of a multi-faceted set of
447 indicators.

448

## 449 Authors contributions:

450 David Navarro-Miró designed the work, collected and analysed the data, interpreted the results, and 451 drafted the article. Ileana Iocola, Corrado Ciaccia, Elena Testani, Laura Depalo, Giovanni Burgio, 452 Hanne Lakkenborg Kristensen, Margita Hefner, Kalvi Tamm, Ingrid Bender, Alessandro 453 Persiani, MariangelaDiacono, Francesco Montemurro, KoenWillekens, Hélène Védie, Martina 454 Bavec, Martina Robačer, DonatienneArlotti, Pauline Deltour, Stefaan De Neve, Mesfin Tsegaye 455 Gebremikael, Lourdes Chamorro, Berta Caballero-López, and Alejandro Pérez-Ferrer 456 contributed to the design and management of the experiments and the data collection in each country. 457 Stefano Canali (SoilVeg project coordinator) conceived the transnational, multisite, and multi-season 458 dimensions of the whole experiment and contributed to its design. José M. Blanco-Moreno and F. 459 **Xavier Sans** played a major role in the conception and design of the work, the data analysis and the 460 interpretation of the results, and also helped draft the article. All authors critically revised the final 461 manuscript.

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471	
472	Data Availability statement
473	The authors confirm that the data supporting the findings of this study are available within the article
474	and its supplementary materials.

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Country	Trial	European Climatic Zones	Temperature rainfall (annual mean)	Soil type	Cash crop	ASC composition	Explanatory variables in the models	Experimental design	Repetitions per treatment
BE-CRA-W	FtA	Atlantic Central	1Y: 10.99 °C; 538 mm	Silt loam	Red cabbage	L or G	T; B	S-P	Four
BE-ILVO	FtA	Atlantic Central	1Y: 11.1 °C; 898 mm 2Y: 11.3 °C; 822 mm	Sandy loam	White cabbage	L and G	T; B; Y	SS-P	Four
BE-INAGRO	FtA	Atlantic Central	1Y: 11.0 °C; 860 mm 2Y: 11.3 °C; 697 mm	Sandy loam	White cabbage	L or G	T; Y; A	S-P	Four
DK	FtA	Atlantic North	1Y: 9.3 °C; 614 mm 2Y: 9.1 °C; 673 mm	Sandy loam	White cabbage	L or G	T; B; Y	S-P	Three
EE	FtA	Nemoral	1Y: 6.0 °C; 825 mm 2Y: 5.8 °C; 694 mm	Sandy clay loam	White Cabbage	L or G	T; B; Y; F	ST-P	Three
50	FtA	Mediterranean North	1Y: 16.5 °C; 406 mm 2Y: 16.1 °C; 409 mm	Loamy	Green pepper	L or G	T; B; Y	R-S-P	Four
Eð	FtB	Mediterranean North	1Y: 16.1 °C; 344 mm 2Y: 16.5 °C; 406 mm	Loamy	Savoy cabbage	L or G	T; B; Y	R-S-P	Four
FR	FtA	Mediterranean North	1Y: 15.5 °C; 521 mm 2Y: 15.3 °C; 558 mm	Clay loamy	Butternut squash	L or G	T; B; Y	R-S-P	Three
	FtA	Mediterranean North	1Y: 16.7 °C; 539 mm 2Y: 16.5 °C; 402 mm	Clay	Tomato	L and G	T; B; Y; F	SS-P	Three
11	FtB	Mediterranean North	1Y: 16.6 °C; 470 mm 2Y: 16.7 °C; 539 mm	Clay	Cauliflower	L or G and B	T; B; Y	SS-P	Three
SI	FtA	Alpine South	1Y: 10.9 °C; 1009 mm 2Y: 11.1 °C; 961 mm	Loam	Cauliflower	L or G	T; B; Y; F	SS-P	Four

Table 1. Environmental conditions, cash crops, ASC and factors analysed in each trial. European Climatic Zones according to Metzger et al. (20
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FtA: Spring-summer cash crop; FtB: Autumn-winter cash crop. BE: Belgium; DK: Denmark, EE: Estonia, ES: Spain; FR: France; IT: Italy, and SI: Slovenia. 1Y: first year; 2Y: second year of experimentation. ASC composition: L: Legumes; G: Grasses; B: Brassicaceae. Explanatory variables: T: Termination; B: Total biomass; Y: Year; F: Fertilization; A: ASC composition. Experimental design: SS-P: Split-split-plot randomized complete block design; S-P: Split-plot randomized complete block design; R-S-P: Randomized strip-plot.

9 Table 2. Ecological and environmental indicators. Estimates (± standard error) and their statistical significance taken from the models evaluating the environmental 10 performance that compared T-GM to NT-RC. Variable transformation codes: †: logarithmic; ††: square root; †††: cube root. Significance codes: 'N.S.' P > 0.05; '\*' P  $\leq 0.05$ ; '\*\*' P  $\leq 0.01$ ; '\*\*\*' P  $\leq 0.001$ . 11

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			Ecological indicators	Environmental indicators			
Country	Trial	Carabidae AD	Staphylinidae AD	Araneae AD	PRE-EUE	N leaching	Beta- glucosidase
BE-CRA-W	FtA					1.93 ± 0.91 *	
BE-ILVO	FtA	11.2 ± 2.63 **	-1.29 ± 0.43 *		$0.37 \pm 0.06$		
BE-INAGRO	FtA					$1.39 \pm 1.27$ N.S.	$0.06 \pm 0.05$ N.S.
DK	FtA	$^{\dagger\dagger\dagger}_{**} 0.58 \pm 0.17$	$-0.92 \pm 1.69$ N.S.	-3.58 ± 1.06 **	$0 \pm 0$ N.S.	$3.43 \pm 1.19$ N.S.	$-5.4 \pm 6.49$ N.S.
EE	FtA				$-0.01 \pm 0.01$ N.S.	†† -0.2 ± 0.17 N.S.	
	FtA				$0.02 \pm 0.01$ *		
ES	FtB			$\begin{array}{c} 2.82 \pm 2.58 \\ \text{N.S.} \end{array}$	$0 \pm 0$ N.S.		
FR	FtA				$0.02 \pm 0$ ***		
T	FtA	0.53 ± 0.23 *	0.79 ± 0.26 **	$-0.17 \pm 0.1$ N.S.	$0 \pm 0$ *	$-0.32 \pm 2.51$ N.S.	$0.34 \pm 0.36$ N.S.
11	FtB	0.37 ± 0.13 **	0.71 ± 0.13 ***	$-0.09 \pm 0.1$ N.S.	$-0.02 \pm 0$ **		
SI	FtA	$-26.25 \pm 4.95 ***$	$\dagger$ -0.66 ± 0.27 *	-8.97 ± 3.08 *			

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Country abbreviations as in Table 1. Ecological indicators: Carabidae AD: activity density of ground beetles; Staphylinidae AD: activity density of rove beetles; Araneae AD: activity

density of spiders; Environmental indicators: PRE-EUE: energy-use efficiency using the potentially recyclable energy as the output of the cropping system; N leaching: nitrogen leaching

15 16 potential. The estimate represents the average difference in the response variable (or its transformation) between NT-RC and T-GM. Positive values imply higher value of the response in 17 NT-RC than in T-GM.

18	Table 3. Agronomic indicators. Estimates (± standard error) and their statistical significance in the models
19	evaluating the agronomic performance that compared T-GM to NT-RC. Variable transformation codes: †:
20	logarithmic; $\dagger \dagger$ : square root. Significance codes: 'N.S.' P > 0.05; '*' P $\leq$ 0.05; '*' P $\leq$ 0.01; '**' P $\leq$ 0.001.
21	

			Agronomic	indicators	
Country	Trial	Weed density	Marketable yield	Cash crop quality	M-EUE
BE-CRA-W	FtA	-785.13 ± 85.32 ***	$-0.22 \pm 0.19$ N.S.	-44.52 ± 3.48 ***	
<b>BE-ILVO</b>	FtA				$0.04 \pm 0.2$ N.S.
<b>BE-INAGRO</b>	FtA		$-4.12 \pm 0.15$ ***		
DK	FtA	-474.94 ± 39.13 ***	† -0.2 ± 0.04 **		<b>††</b> -0.17 ± 0.03
EE	FtA	-140.08 ± 41.38 **	†† -0.27 ± 0.08 **	<b>††</b> -1.77 ± 1.14 N.S.	<b>††</b> -0.19 ± 0.06 **
ES	FtA	<b>††</b> -10.98 ± 5.27 *	$0.26 \pm 0.15 \text{ N.S}$	$0.55 \pm 0.43$ N.S.	$0.14 \pm 0.05$ *
E3	FtB	<b>†</b> -0.77 ± 0.1 ***	$-1.3 \pm 0.4 **$	$1.37 \pm 1.17$ N.S.	-0.34 ± 0.1 **
FR	FtA	† -1.68 ± 0.26 ***	$-1.91 \pm 0.24$ ***	$-0.93 \pm 0.15$ ***	-0.44 ± 0.11 **
IT	FtA	$0.12 \pm 0.16$ N.S.	$0.32 \pm 0.15$ N.S.	$-0.26 \pm 0.08$ **	† 0.37 ± 0.15 *
11	FtB	$25.44 \pm 12.79$ N.S.	$-0.23 \pm 0.12$ N.S.	$-0.01 \pm 0.4$ N.S.	$-0.11 \pm 0.07$ N.S.
SI	FtA	†† -8.99±0.34 ***			

Country abbreviations as in Table 1. Agronomic indicators: M-EUE: energy-use efficiency using the marketable yield as the output of the cropping system. The estimate represents the average difference in the response variable (or its transformation) between NT-RC and T-GM. Positive values imply higher value of the response in NT-RC than in T-GM. Figure 1. Graphical representation of the statistical support for the differences in environmental and agronomic performance between T-GM and NT-RC. The bars represent the Z value obtained from the weighted Stouffer's test across trials for each indicator. Significance codes: 'N.S.' P > 0.05; '\*'  $P \le 0.05$ ; '\*'  $P \le 0.01$ ; '\*\*\*'  $P \le 0.001$ .



ASC management strategies: no-till roller crimping (NT-RC) and green manuring (T-GM). Ecological indicators: Carabidae AD: activity density of ground beetles; Staphylinidae AD: activity density of rove beetles; Araneae AD: activity density of spiders; Environmental indicators: PRE-EUE: energy-use efficiency using the potentially recyclable energy as the output of the cropping system; N leaching: nitrogen leaching potential; Beta-glucosidase enzyme. Agronomic indicators: M-EUE: energy-use efficiency using the marketable yield as the output of the cropping system.
## **1** Appendix S1. Trial details

2 This Appendix describes all experiments carried out in all trials located in all seven European
3 countries. Our study compared only the no-till roller crimping (NT-RC) and tilling as green
4 manure (T-GM) of agroecological service crop (ASC) management strategies.

# 5 Belgium - Walloon Agricultural Research Center (BE-CRA-W)

### 6 Field experiment type A

#### 7 Experimental design

8 The field trial was newly established at the Walloon Agricultural Research Center located in 9 Gembloux, Belgium (BE-CRA-W) (50° 36' 35.45" N and 4° 57' 14.91" E). This location 10 represented the Atlantic Central European climatic zone. During experimentation, the mean 11 annual temperature and rainfall were 10.99 °C and 538 mm, respectively. The trial soil had a silt 12 loam texture and 0.91 % organic carbon content.

In this trial, only data from the second cycle (2016–2017) were gathered. During the first cycle (2015–2016), poor weather conditions delayed cabbage planting by 8 weeks which caused a significant decline in the survival and quality of the cabbage seedlings. Owing to the challenge of obtaining new cabbage seedlings quickly, and in consideration of financial loss to the farmer, the first year of the trial was abandoned.

The experimental field was located in an area managed according to European organic farming regulations since 1995. The previous crop was a mixture of oat (*Avena sativa* L.) and pea (*Pisum sativum* L.). The trial design was a split-plot with four replications, where ASC composition was the subplot factor, and the whole-plot factor was ASC management (Figure 1).

22



2016-2017 SoilVeg FTA field experiment of CRA-W



The three ASC compositions were ASC1: 50 % barley (Hordeum vulgare L.) + 50 % pea 29 (Pisum sativum), ASC2: 70 % barley (H. vulgare) + 30 % pea (P. sativum), and ASC3: 100 % 30 31 barley (*H. vulgare*). The three ASC management strategies were: (1) chopped and incorporated into the soil by tillage as green manure (T-GM), (2) chopped and not incorporated into the soil 32 (BN), and (3) flattened by roller-crimping (NT-RC). In parallel, a control treatment without 33 plant cover (bare soil, BS) was established. The roller crimper was 3 m wide and weighed 34 35 1,720 kg (Picture 1.A). In the NT-RC plots, furrows for cash crop transplanting were created using an in-line tillage (Picture 1.B). Plot size was  $3 \times 9$  m. The cash crop was red cabbage 36 (Brassica oleracea var. capitata L. f. rubra). 37

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40	Picture 1. Machinery used for NT-RC management in the Walloon Agricultural Research Center (BE-CRA-W) trial
41	A - Roller crimper; B - In-line tiller.

#### 42 Agronomic management

On the 25<sup>th</sup> August 2016, before ASC sowing, 20 t ha<sup>-1</sup> of cow manure (82 kg total N ha<sup>-1</sup>) was applied as fertiliser. The ASCs were sown on the 15<sup>th</sup> September 2016. In BS plots, four weed control operations, using a rotary harrow, were carried out during the ASC growth period. To simulate farmer practise, ASC termination was carried out on different dates, depending on the ASC management strategy: T-GM on May 5<sup>th</sup>, CNI on May 23<sup>rd</sup>, and NT-RC on May 31<sup>st</sup>, 2017.

Red cabbage was transplanted on the 31<sup>st</sup> May 2017, with a row spacing of 0.60 m and a plant spacing of 0.40 m (Picture 2). This cash crop was fertilised during planting, using commercial organic fertiliser containing 60 kg ha<sup>-1</sup> of nitrogen and 33 kg ha<sup>-1</sup> of phosphorous. Manual weed control was performed during growth of the cash crop on the 14<sup>th</sup> July 2017 only in T-GM and BS plots. The mulch in CNI and NT-RC plots provided acceptable weed control. The cash crop did not require irrigation and was harvested manually on the 25<sup>th</sup> and 26<sup>th</sup> of October 2017.



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56 Picture 2. View of the red cabbage cash crop in the Walloon Agricultural Research Center (BE-CRA-W) trial.

57 More information about this trial can be found in Arlotti, Lakkenborg Kristensen, Canali, De

58 Neve, Huyghebaert, et al. (2019), Arlotti, Lakkenborg Kristensen, Canali, De Neve, Sans Serra,

59 et al. (2019) and Hefner, Canali, et al. (2020).

#### Belgium - Research Institute for Agriculture, Fisheries and Food (BE-60

ILVO) 61

#### Field experiment type A 62

#### **Experimental design** 63

The field trial was newly established at the Research Institute for Agriculture, Fisheries and 64 Food (ILVO) in Merelbeke, Belgium (BE-ILVO) (50° 59' 38" N and 3° 44' 46" E), located in 65 the Atlantic Central European climatic zone. During the first (2015-2016) and second (2016-66 2017) cycles, the mean annual temperature and rainfall were 11.1 °C and 898 mm, and 11.3 °C 67 and 822 mm, respectively. The trial soil had a sandy loamy texture. 68

The experiment was repeated on the same plots during both years. The trial had a split-split-plot 69 randomised complete block design with two factors and four replications. The main plot was the 70

- ASC management strategy, and the application of compost was the subplot factor (Figure 2). 71



Figure 2 Experimental design of the Research Institute for Agriculture, Fisheries and Food (BE-ILVO) trial.

74 Termination: R RT ASC-GM = ASC chopped and incorporated into the soil (T-GM); R RT ASC-RC = ASC flattened by a roller crimper (NT-RC); and R\_RT\_noASC = Control treatment without ASC. Compost factor: White No application of compost; Grey - Application of compost.

The ASC termination strategies were: (1) roller-crimped (NT-RC), (2) chopped with a flail mower and incorporated into the soil by non-inversion tillage (T-GM). The roller crimper was 3.1 m wide, weighed 1,720 kg when filled with oil, and was designed and constructed by ILVO (Picture 3). In the NT-RC plots, furrows for cash crop transplanting were created with a harrow tooth. The ASC was a mixture of 40 % rye (*Secale cereale* L.) and 60 % pea (*Pisum sativum*). Plot size was 7.5 × 15 m. The cash crop was white cabbage (*Brassica oleracea* var. *capitata* L.).



84

85 Picture 3. The roller crimper flattening the ASC in the Research Institute for Agriculture, Fisheries and Food
86 (BE-ILVO) trial.

#### 87 Agronomic management

The ASC was sown on the 5<sup>th</sup> October 2015, and the 24<sup>th</sup> November 2016. In T-GM plots, the 88 ASC was terminated by flail mowing on the 20th April 2016 and the 7th May 2017, and by 89 superficial tillage on the 4th May 2016 and the 8th May 2017. The NT-RC plots were terminated 90 on the 26<sup>th</sup> May 2016 and the 16<sup>th</sup> June 2017. The cash crop was transplanted and fertilised 91 using a planting machine on the 27<sup>th</sup> May 2016, and the 21<sup>st</sup> June 2017 (Picture 4). Mechanical 92 weeding was carried out on the 6th June, 6th, 26th, and 27th July 2016, and on the 13th, 17th, and 93 27<sup>th</sup> July 2017. Manual weeding was carried out during the periods: 6<sup>th</sup> to 22<sup>nd</sup> July, 28<sup>th</sup> July to 94 4th August, and 5th to 14th September 2016, and on the 14th, 27th, and 28th July 2017. Cash crop 95

- 96 irrigation was only required during the second year and was conducted manually twice during
- 97 the crop cycle. The cash crop harvest was performed on the 3<sup>rd</sup> and 4<sup>th</sup> November 2016, and the
- 98 7<sup>th</sup> November 2017.



99

Picture 4. Transplanted white cabbage in an NT-RC plot in the Research Institute for Agriculture, Fisheries, and
 Food (BE-ILVO) trial.

- 102 More information about this trial can be found in Witvrouw (2016), Navarro-Miró, Iocola, et al.
- 103 (2019) and Hefner, Canali, et al. (2020).

## 104 Belgium - INAGRO (BE-INAGRO)

## 105 Field experiment type A

#### 106 Experimental design

107 The field trial was newly established at the INAGRO organic farm station in Roeselare,

108 Belgium (BE-INAGRO) (50° 90' 68" N and 3° 12' 72" E), located in the Atlantic Central

109 European climatic zone. During the first (2015–2016) and second (2016–2017) cycles, the mean

110 annual temperature and rainfall were 11.0 °C and 860 mm, and 11.3 °C and 697 mm,

respectively. The trial soil had a sandy loamy texture and a 1.12 % organic carbon content.

112 The experiment was not repeated on the same plots in both years, and was moved to an adjacent

area for the 2016–2017 cycle. The INAGRO trial farm has been managed according to organic

114 farming regulations since 2003 and has a rotation over six years (grass-clover, leek,

carrot/celeriac, cereals, cabbage, and potato). The trial design was a split plot with four 115



replications. The experimental design was modified each year (Figures 3 and 4). 116

- 120 Termination: RC early - Roller crimper early termination; RC late - Roller crimper late termination; and GM - Mill
- 121 cutting and non-inversion tillage (T-GM). ASC composition: A - winter rye (Secale cereale), B - pea
  - (Pisum sativum); C rye-pea mixture; and Blank No ASC.

123

122





126 Figure 4. Experimental design at the INAGRO (BE-INAGRO) organic farm station during the second year. 127 Termination: GM (white) - Incorporation by mill cutting one month before planting (T-GM); Mulch (red) - Mulching 128 by flail mowing at planting (not-incorporated); and RC (yellow) - Roller crimper (NT-RC). ASC composition: A 129 (vertical lines) - Winter rye (Secale cereale); B (small dots) - Winter pea (Pisum sativum); and C (no pattern) Rye-130 pea mixture.

131 The ASC compositions were A: winter rye (Secale cereale), B: winter pea (Pisum sativum) and C: a rye-pea mixture. The second factor was the ASC management strategy. During the first 132 year, the ASC management strategies analysed were: (1) roller crimper early termination, (2) 133 roller crimper late termination, and (3) mill cutting and non-inversion tillage, one month before 134 planting (T-GM). The roller crimper early termination treatment was scheduled to coincide with 135 the time of pea flowering (i.e., one week before cash crop transplanting) and the roller crimper 136 late termination treatment, at the time of rye flowering (i.e., one day before planting of the cash 137 crop). In the second year, the ASC management strategies studied were: (1) incorporation by 138 mill cutting (MC) one month before planting (T-GM), (2) mulching by flail mowing at planting 139

(not-incorporated), and (3) roller crimping (NT-RC). In this trial, the roller crimper used for ASC management was the same as in the ILVO trial (Picture 5.A) and furrows for cash crop transplanting were created by in-line tillage (Picture 5.B). Additionally, during both years, a control treatment that did not use ASC and standard soil management was set-up. Plot size was  $6 \times 10$  m (except the fallow plots:  $6 \times 9$  m) during the first year and  $3 \times 15$  m during the second year. The cash crop was white cabbage (*Brassica oleracea* var. *capitata*).

A)

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Picture 5. Machinery used for NT-RC management at the INAGRO (BE-INAGRO) organic farm station. A - Roller
 crimper; B - In-line tiller.

#### 149 Agronomic management

The trial was fertilised with composted farm yard manure (10 ton ha <sup>-1</sup>) on October 12<sup>th</sup>, 2015, and with commercial organic fertiliser (Organic plant feed (OPF) granulate 11-0-5, Plant Health Cure B.V., Nederland) on March 16<sup>th</sup>, 2017. The ASC was sown on October 13<sup>th</sup>, 2015 and October 28<sup>th</sup>, 2016. During the first year, the ASC was terminated with the T-GM strategy on April 28<sup>th</sup>, 2016 and with the NT-RC strategy on May 23<sup>rd</sup>, 2016. During the second year, termination happened on April 18<sup>th</sup>, 2017 in the T-GM plots, and on May 24<sup>th</sup>, 2017 in the NT-RC plots.

White cabbage was transplanted, with a row spacing of 0.70 m and a plant spacing of 0.30 m, using a planting machine on May 25<sup>th</sup>, 2016 and on May 30<sup>th</sup>, 2017 (Picture 6). The cabbages were fertilised with 50 kg N ha<sup>-1</sup> commercial organic fertiliser (OPF granulate 11-0-5) on July 8<sup>th</sup>, 2016, during the first cycle, and on May 31<sup>st</sup>, 2017 during the second cycle. The cash crop was irrigated on August 24<sup>th</sup>, and 31<sup>st</sup>, 2016, and only once at the time of cash crop transplantation in 2017. In NT-RC plots, weeding operations were not required during the cash crop cycle. In T-GM plots, in the first year, weeding operations during the cash crop cycle were carried out by hoeing (June 8<sup>th</sup>, 2016) harrowing (June 9<sup>th</sup>, 2016) and manually (July 20<sup>th</sup>, and 22<sup>nd</sup>, 2016). In the second year, T-GM plots were weeded by mechanical weed control (June 15<sup>th</sup>, 2017) and manually (June 15<sup>th</sup>, and July 6<sup>th</sup>, 2017). The cash crop harvest was performed on November 21<sup>st</sup>, 2016 and November 7<sup>th</sup>, 2017. More information about this trial can be found

168 in Hefner, Canali, et al. (2020).



Picture 6. Transplanting of white cabbage using a planting machine at the INAGRO (BE-INAGRO) organic farm
 station.

# 172 Denmark (DK)

169

#### 173 Field experiment type A

#### 174 Experimental design

The field trial was newly established at the Department of Food Science research centre of Aarhus University, located in Årslev, Denmark (55° 18' N and 10° 27' E), in the Atlantic North European climatic zone. The mean annual temperature was 9.3 °C and the mean annual rainfall, 614 mm during the first cycle (2015–2016), and 9.1 °C and 673 mm during the second cycle (2016–2017), respectively. The soil had a sandy loamy texture and a 1 % organic carbon content. The experiment was not repeated on the same plots in both years, and was moved to an adjacent area for the 2016–2017 cycle. The two locations had been managed according to Danish organic farming regulations since 1996 and 2014, respectively. The previous crop grown in the area was barley (*Hordeum vulgare* L.). The trial had a split-plot randomised complete block experimental design with three replications, where ASC management was the whole-plot factor and ASC composition, the subplot factor. The experimental design was modified each year (Figures 5 and

187 6).



- incorporated into the soil with a cultivator as green manure (T-GM); 2 (orange) Roller-crimped (NT-RC); and 3
- 193 (yellow) Strip cultivation/strip green manure between rows of crop. ASC composition: A No ASC, winter fallow
- 194 (bare soil); B Winter faba bean; C Winter pea, D Winter vetch; E 50/50 mixture of winter rye and winter faba
- 195 bean; F 50/50 mixture of winter rye and winter pea; and G 50/50 mixture of winter rye and winter vetch.



Figure 6. Experimental design of the organic farm station of the Department of Food Science research center of
Aarhus University (DK) during the second cycle (2016–2017). Termination: 1 (green) - Chopped with a flail mower
and incorporated into the soil with a cultivator as green manure (T-GM); 2 (orange) - Roller-crimped (NT-RC). ASC
composition: A - No ASC, winter fallow (bare soil); B - Winter faba bean; C - Winter pea, D - Winter vetch; E 50/50 mixture of winter rye and winter faba bean; F - 50/50 mixture of winter pea; and G - 50/50
mixture of winter rye and winter vetch.

The ASC termination strategies were: (1) chopped with a flail mower and incorporated into the 204 soil with a cultivator as green manure (T-GM), (2) roller-crimped (NT-RC), and (3) strip 205 cultivation/strip green manure between crop rows (additive design). The roller crimper was 2 m 206 wide and weighed 932 kg. It was designed and constructed by Soldo Macchine Agricole 207 208 (Grassano, Italy) (Picture 7.A). Furrows for cash crop transplanting in the NT-RC plots were created with a harrow tooth (Picture 7.B). The ASC species composition was: B: winter faba 209 bean (Vicia faba L.), C: winter pea (Pisum sativum), D: winter vetch (Vicia sativa L.), E: 50/50 210 mixture of winter rye (Secale cereale) and winter faba bean, F: 50/50 mixture of winter rye and 211

winter pea, and G: 50/50 mixture of winter rye and winter vetch (Picture 8). A control treatment of winter fallow (bare soil) was also included. Plot size was  $3.2 \times 10$  m during the first year and  $4.8 \times 10$  m during the second year. The cash crop was white cabbage (*Brassica oleracea* var. *capitata*).



216

Picture 7. Machinery used for NT-RC management in the DK trial. A - Roller crimper; B - Harrow tooth used to
 create the cash crop transplanting furrows.

## 219 Agronomic management

- 220 The trial was fertilised with 200 kg ha<sup>-1</sup> of feather meal pellets (N-P-K: 13-0-0.4) (26 kg N ha<sup>-1</sup>)
- on September 9<sup>th</sup>, 2015 and September 28<sup>th</sup>, 2016. The ASCs were sown on October 5<sup>th</sup>, 2015
- and October 9th, 2016 and terminated on June 10th, 2016 and May 30th, 2017 (Picture 8).



223 224

Picture 8. View of DK field trial before ASC termination.

White cabbage was transplanted using a three-row planting machine on July 1<sup>st</sup>, 2016, and on June 21<sup>st</sup>, 2017, with a row spacing of 0.5 m and a plant spacing of 0.5 m. Weed management

was carried out in T-GM plots using a weed-brush machine in inter-rows on July 27th-29th and 227 August 19th, 2016, and July 17th–19th, 2017, and manually with a hoe in inter-rows and intra-228 rows on September 26th-30th, 2016 and August 10th-22nd, 2017. In NT-RC plots, weeding 229 operations consisted of the manual removal of above ground biomass of large weeds. During the 230 first year, cabbages were fertilised with 50 kg N ha<sup>-1</sup> feather meal pellets on August 25<sup>th</sup>, 2016. 231 During the second year, cash crop fertilisation with 100 kg N ha<sup>-1</sup> feather meal pellets was 232 carried out a week before cabbage transplantation. Thirty kg N ha<sup>-1</sup> lupine seeds (N-P-K: 4.5-233 0.4-0.9) were applied on June 15<sup>th</sup>, 2017, and 80 kg N ha<sup>-1</sup> feather meal pellets on August 24<sup>th</sup>, 234 235 2017. Cash crop irrigation was only required during the first year and was conducted twice (in August and September) with sprinklers. The cabbage crop was harvested on November 11<sup>th</sup>, 236 2016, and November 2<sup>nd</sup>, 2017. 237

More information about this trial can be found in Navarro-Miró, Iocola, et al. (2019) NavarroMiró, Blanco-Moreno, et al. (2019), Hefner, Gebremikael, et al (2020) and Hefner, Canali, et al.
(2020).

# 241 Estonia (EE)

### 242 Field experiment type A

#### 243 Experimental design

The field trial was newly established in an experimental organic research field at Jõgeva in eastern Estonia (EE) (58° 44' N and 26° 24' E), located in the Nemoral European climatic zone. In the first cycle (2015–2016), the mean annual temperature was 6.0 °C and the mean annual rainfall, 825 mm, and in the second cycle (2016–2017) these environmental factors were 5.8 °C and 694 mm, respectively. The trial soil had a clay loamy texture and a 3 % organic carbon content.

The experiment was not repeated in the same plots in both years, and was moved to an adjacent area for the 2016–2017 cycle. The trial was established in an area certified organic from 2005. The previous crop grown in the area was red clover (*Trifolium pratense* L.). The trial had a 253 strip-plot design with ASC strips and ASC management strategies crossed with a fertiliser



factor, and three replicates per treatment (Figure 7).

255

Figure 7. Experimental design of the research field at the organic farm station at Jõgeva in eastern Estonia (EE).
Termination: RC - Roller-crimped (NT-RC); and GM - Chopped by a flail mower, then ploughed and levelled by a
cultivator (T-GM). ASC composition: ASC1 - 100 % Winter rye; and ASC2 - 100 % Winter triticale. NoA - Control
treatment without ASC (No ASC). Fertiliser factor: 1) Application of 30 t ha<sup>-1</sup> solid cattle manure; 2) Not fertilised.

The two ASC termination strategies were: (1) roller-crimped (NT-RC), and (2) chopped by a 260 flail mower, then ploughed, and levelled by a cultivator (T-GM). The roller crimper was 2 m 261 wide and weighed 800 kg during the first year ASC termination, and 1,200 kg during the 262 second, and was designed and constructed by Soldo Macchine Agricole (Grassano, Italy) 263 (Picture 9). In the NT-RC plots, furrows for cash crop transplanting were created by in-line 264 tillage (Picture 9). The ASC species composition was: ASC1 - 100 % winter rye (Secale 265 cereale) (180 kg ha<sup>-1</sup>), and ASC2 - 100 % winter triticale (× Triticosecale blaringhemii 266 A.Camus) (155 kg ha<sup>-1</sup>). The fertilisation factor consisted of: (1) application of 30 t ha<sup>-1</sup> solid 267 cattle manure (153 kg ha<sup>-1</sup> N, 57 kg ha<sup>-1</sup> P, and 81 kg ha<sup>-1</sup> K), and (2) no fertiliser. Plot size was 268  $6 \times 4$  m. The cash crop was white cabbage (*Brassica oleracea* var. *capitata*). 269



270

271 Picture 9. Machinery used for NT-RC management in the organic research field at Jõgeva in eastern Estonia (EE). A
 272 tractor equipped with a roller crimper and an in-line tiller.

### 273 Agronomic management

274 Fertiliser was applied to the fertiliser treatment plots before the ASCs were planted. During the second year, in addition to the fertilisation factor, all plots were fertilised with 12 t ha-1 of horse 275 manure compost (12 kg ha<sup>-1</sup> N, 1.2 kg ha<sup>-1</sup> P, and 4.8 kg ha<sup>-1</sup> K). During the first cycle, the 276 ASCs were sown on August 25th, 2015 and terminated by NT-RC on June, 6th and June 9th, 277 278 2016, and by T-GM on June 10th, 2016. During the second cycle, the ASCs were sown in September 2016 and managed by T-GM on June 16th, 2017 and by NT-RC on June 19th, 2017. 279 White cabbage was manually transplanted in the first year from the 13<sup>th</sup> to 16<sup>th</sup> June 2016, and 280 in the second year on June 19th, 2017, with a row spacing of 0.65 m and a 0.50 m plant spacing 281 (Picture 10). Manual weeding was carried out in all treatments on August 27th, 2016 and July 282

**283** 27<sup>th</sup>, 2017.



284

**285 Picture 10.** View of the organic farm station field at Jõgeva in eastern Estonia (EE) during growth of the cash crop.

During the first year, the cash crop was not irrigated, whereas during the second year, all plants were watered once in mid-July with a humic solution (0.0003 kg ha<sup>-1</sup> N, 0.0001 kg ha<sup>-1</sup> P, and 0.0002 kg ha<sup>-1</sup> K). The cash crop harvest was performed on October 7<sup>th</sup>, 2016, and from October 4<sup>th</sup> to 6<sup>th</sup>, 2017.

More information about this trial can be found in Tamm, Bender, Nugis, Edesi, & Võsa, (2018),
Navarro-Miró, Iocola, et al. (2019), Navarro-Miró, Blanco-Moreno, et al. (2019) and Hefner,
Canali, et al. (2020).

## 293 Spain (ES)

#### 294 Experimental design

Both parallel field experiments type A (FtA) and type B (FtB) were newly established in the 295 Gallecs Area of Natural Interest, Barcelona, Spain (ES) (41° 33' N and 2° 12' E), located in the 296 Mediterranean North European climatic zone. In FtA, during the first cycle (2015–2016), the 297 mean annual temperature was 16.5 °C and the mean annual rainfall, 406 mm, and during the 298 second cycle (2016–2017), 16.1 °C and 409 mm, respectively. In FtB, during the first cycle 299 (2014–2015), the mean annual temperature was 16.1 °C and the mean annual rainfall, 344 mm, 300 and in the second cycle (2015-2016), 16.5 °C and 406 mm, respectively. The trial soil had a 301 302 loamy texture and contained an average of 0.95 % organic carbon content.

In both trials, the field experiments were repeated in the same area in both years. Conversion of 303 the experimental area to organic farming began in 2005, and the previous crop grown in the area 304 was wheat. The experimental design of the FtA and FtB trials was a randomised strip-plot with 305 306 two factors (ASC composition and ASC management strategy) and four replicates. The different treatments were defined in randomly distributed parallel bands, and within each band, four plots 307  $(6 \times 4 \text{ m})$  were established. The experimental layout was designed to facilitate traffic of 308 machinery between plots and to enable the agricultural practices to be performed in the same 309 310 direction.

In FtA and FtB, the two ASC termination strategies were: (1) ASCs flattened by a roller crimper (NT-RC), and (2) ASCs mown and chopped and incorporated into the soil as green manure using a chisel plough (T-GM). The roller crimper was 3 m wide and weighed 800 kg when filled with oil, and was designed and constructed by Soldo Macchine Agricole (Grassano, Italy) (Picture 11.A). In the NT-RC plots, furrows for cash crop transplanting were created by in-line tillage (Picture 11.B). Both termination methods were compared to a control treatment without ASC (bare soil).



## 328 Field experiment type A

In FtA, three ASC compositions and one No ASC treatment were established: ASC1 – 100 % cereal mixture (81 % *Avena byzantina* K.Koch and 19 % *Hordeum vulgare*) (200 kg ha<sup>-1</sup>), ASC2 - 70 % cereal mixture (140 kg ha<sup>-1</sup>) + 30 % *Vicia sativa* (75 kg ha<sup>-1</sup>), ASC3 - 50 % cereal mixture (100 kg ha<sup>-1</sup>) + 50 % *V. sativa* (125 kg ha<sup>-1</sup>), and No ASC - spontaneous vegetation without sowing any ASC (Figure 8). The cash crop was green pepper (*Capsicum annuum* L.)





Figure 8. Experimental design of field experiment type A established in the Gallecs Area of Natural Interest,
Barcelona, Spain (ES). Termination: ASC-R - Flattened by roller crimper (NT-RC); and ASC-GM - mowed, chopped
and incorporated into the soil as green manure using a chisel plough (T-GM). ASC composition: ASC1 – 100 %
cereal mixture (81 % *Avena byzantina* and 19 % *Hordeum vulgare*); ASC2 - 70 % cereal mixture + 30 % *Vicia sativa*; and ASC3 - 50 % cereal mixture + 50 % *V. sativa*; and No ASC - spontaneous vegetation without sowing any
ASC. BS - control treatment maintaining the soil without plant cover (bare soil).

#### 341 Field experiment type B

In FtB, the ASC compositions were: ASC1 - 100 % *Vigna unguiculata* (L.) Walp., ASC2 - 70 % *V. unguiculata* + 30 % *Sorghum bicolor* (L.) Moench, ASC3 - 50 % *V. unguiculata* + 50 % *S. bicolor*, and No ASC - spontaneous vegetation without sowing any ASC (Figure 9). The cash
crop was savoy cabbage (*Brassica oleracea* L. var. *sabauda*).





Figure 9. The experimental design of the FtB field experiment established in the Gallecs Area of Natural Interest,
Barcelona, Spain (ES). Termination: ASC-R - Flattened by roller crimper (NT-RC); and ASC-GM - mowed, chopped
and incorporated into the soil as green manure using a chisel plough (T-GM). ASC composition: ASC1 - 100 % *Vigna unguiculata*; ASC2 - 70 % *V. unguiculata* + 30 % *Sorghum bicolor*; ASC3 - 50 % *V. unguiculata* + 50 %

*S. bicolor*; and No ASC - spontaneous vegetation without sowing any ASC. BS - control treatment maintaining the
 soil without plant cover (bare soil).

#### 353 Agronomic management

#### 354 Field experiment type A

The ASCs were sown on November 19<sup>th</sup>, 2015 and January 9<sup>th</sup>, 2016. In the NT-RC plots, ASC management was carried out on May 4<sup>th</sup>, 2016 and May 18<sup>th</sup>, 2017, and creation of the transplanting furrows was carried out along with the NT-RC by in-line tillage on June 24<sup>th</sup>, 2016 and June 13<sup>th</sup>, 2017.

In the T-GM plots, ASC chopping was carried out on May 4<sup>th</sup>, 2016 and May 18<sup>th</sup>, 2017, and the 359 incorporation of the plant material into the soil was performed on May 18<sup>th</sup>, 2016 and June 1<sup>st</sup>, 360 2017. The green pepper crop were transplanted on May 26<sup>th</sup>, 2016, and on June 20<sup>th</sup>, 2017, with 361 a row spacing of 0.80 m and a 0.50 m plant spacing (Picture 12). The cash crop was fertilised 362 just after transplantation with 170 kg ha<sup>-1</sup> N using commercial organic fertiliser and the green 363 pepper plants were drip-irrigated according to their needs. During the first year, T-GM plots 364 were weeded four times, whereas NT-RC plots only required two weeding operations. During 365 the second year, all plots required three weeding operations. In the first year, the cash crop 366 harvest was performed weekly from July 18th to October 3rd, 2016, whereas in the second year 367 the harvest took place from August 21st to October 2nd, 2017. 368



#### **370 Picture 12.** View of the FtA field experiment established in the Gallecs Area of Natural Interest, Barcelona, Spain

(ES) during growth of the cash crop.

371

369

#### 372 Field experiment type B

373 The ASCs were sown on April 30<sup>th</sup>, 2015 and on May 4<sup>th</sup>, 2016, and irrigated with sprinklers during their development. During the first cycle, the ASCs were managed by two passes of NT-374 RC on July 23<sup>rd</sup> and 27<sup>th</sup>, 2015 and one operation combining NT-RC and in-line tillage on July 375 29th, 2015. In the T-GM plots, the ASCs were chopped on July 23rd, 2015 and incorporated into 376 the soil using a chisel plough on July, 28<sup>th</sup>, 2015. During the second cycle, NT-RC management 377 was carried out on August 26th, 2016, and the creation of the transplanting furrows was carried 378 out along with the NT-RC by in-line tillage on September 6<sup>th</sup>, 2016. In the T-GM management 379 plots, chopping of the ASC was carried out on August 26<sup>th</sup>, 2016, and incorporation of plant 380 material into the soil was performed on September, 6<sup>th</sup>, 2016. The savoy cabbages were 381 transplanted on August 4<sup>th</sup>, 2015, and September 20<sup>th</sup>, 2016, with a row spacing of 0.80 m and a 382 0.50 m plant spacing (Picture 13). The cash crop was fertilised with 100 kg ha<sup>-1</sup> N in both years. 383 During the first year, the commercial organic fertiliser was split into two applications: (1) just 384 after savoy cabbage transplantation and (2) during savoy cabbage development. During the 385 second year, the commercial organic fertiliser was applied just after the savoy cabbage was 386 387 transplanted. The cabbages were drip irrigated according to the crop needs. In the first cycle, all plots were weeded only once during the cash crop development, whereas in the second year, 388 two weeding operations were required. The savoy cabbages were harvested on December 2<sup>nd</sup>, 389 2015, and February 22<sup>nd</sup>, 2017. 390



391

393

392 Picture 13. Transplanted savoy cabbage in a NT-RC plot in the FtB field experiment established in the Gallecs Area

of Natural Interest, Barcelona, Spain (ES).

394 More information about this trial can be found in Navarro-Miró et al. (2017), Navarro-Miró,

395 Iocola, et al. (2019), and Navarro-Miró, Blanco-Moreno, et al. (2019).

## 396 France (FR)

#### 397 Field experiment type A

#### 398 Experimental design

The field experiment was newly established at the experimental organic research centre of the Groupe de Recherche en Agriculture Biologique (GRAB) in Avignon, southern France (FR) (43° 54' 23.8" N and 4° 53' 06.4" E). This location represented the Mediterranean North European climatic zone. During the first cycle (2015–2016), the mean annual temperature was 15.5 °C and the mean annual rainfall, 521 mm, and in the second cycle (2016–2017) these environmental factors were 15.3 °C and 558 mm, respectively. The trial soil had a clay loam texture and a 1.86 % organic carbon content.

The experiment was repeated on the same plots in both years, but with some changes in the second year. The selected experimental field had been under organic farming management from 2000. The previous crops grown were diversified varieties of squash (*Cucurbita* sp.). The trial had a randomised strip-plot experimental design with three replicates during the first year and four during the second year, where ASC management strategy (i.e., NT-RC or T-GM) was the strip factor, and the ASC composition was the subplot factor (i.e., six different ASC compositions). The experimental design was modified each year (Figures 10 and 11).



419 ASC1 - 50 % Secale cereale + 50 % Pisum sativum; ASC2 - 30 % S. cereale + 40 % Vicia faba + 40 % Vicia villosa;

420 ASC3 - 50 % Hordeum vulgare + 37 % V. faba + 40 % P. sativum; and Control - Control treatment maintaining the

421 soil without plant cover (bare soil).



424 Figure 11. Second cycle (2016–2017) experimental design of the trial established at the experimental organic 425 research centre of the Groupe de Recherche en Agriculture Biologique (GRAB) in Avignon (FR). Termination: RC -426 Cover crop flattened by a roller crimper + in-line tillage to create the transplanting furrows (NT-RC); and GM -427 Termination as a green manure by mowing, chopping, and incorporation of the cover crop into the soil (T-GM). ASC 428 composition: ASC1 - 50 % Secale cereale + 50 % Pisum sativum; and ASC3 - 50 % Hordeum vulgare + 37 % Vicia 429 faba + 40 % P. sativum. Additionally, two Control treatments maintaining the soil without plant cover (bare soil) 430 were established: ST-control - Strip tillage before cash crop transplantation; and GM-control. 431 The two ASC termination strategies were: (1) cover crop flattened by a roller crimper (NT-RC) + in-line tillage to create the transplanting furrows, and (2) termination as a green manure by 432 mowing, chopping, and incorporation of the cover crop into the soil (T-GM). The roller crimper 433

was 2.21 m wide and weighed 600 kg. During the second cycle, four blocks of concrete (i.e.
70 kg each) were added to increase the weight of the roller to 920 kg (Picture 14). The roller

436 crimper used in the FR trial was self-built in co-operation with *L'atelier Paysan*. During the

first year, the ASC species composition was: ASC1: 50 % Secale cereale (60 kg ha<sup>-1</sup>) + 50 % 437 *Pisum sativum* (80 kg ha<sup>-1</sup>), ASC2: 30 % *S. cereale* (40 kg ha<sup>-1</sup>) + 40 % *Vicia faba* (80 kg ha<sup>-1</sup>) + 438 40 % Vicia villosa Roth (20 kg ha<sup>-1</sup>), and ASC3: 50 % Hordeum vulgare (50 kg ha<sup>-1</sup>) + 37 % V. 439 faba (73 kg ha<sup>-1</sup>) + 40 % P. sativum (67 kg ha<sup>-1</sup>). In the second year, only two of the previous 440 ASC compositions were sown: ASC1 - 50 % S. cereale (60 kg ha<sup>-1</sup>) + 50 % P. sativum (80 kg 441 ha<sup>-1</sup>), and ASC3 - 50 % H. vulgare (50 kg ha<sup>-1</sup>) + 37 % V. faba (73 kg ha<sup>-1</sup>) + 40 % P. sativum 442 (67 kg ha<sup>-1</sup>). Plot size was  $10 \times 6$  m during the first year and  $10 \times 5$  m during the second year. 443 The cash crop was butternut squash (Cucurbita moschata Duchesne cv. 'Ariel'). 444



445

446 Picture 14. Machinery used for NT-RC management at the experimental organic research centre of the Groupe de
447 Recherche en Agriculture Biologique (GRAB) in Avignon (FR). A tractor equipped with a roller crimper and an in448 line tiller.

#### 449 Agronomic management

450 The trial was fertilised with 2 t ha<sup>-1</sup> of organic commercial fertiliser (AB'Flor, N-P-K: 6-7-10)

451 and 6 t ha<sup>-1</sup> of compost (with approximately 65 % green waste and 35 % horse manure). ASCs

452 were sown on October 1st, 2015 and October 11th, 2016. ASCs were terminated on April 26th,

453 2016 in the T-GM plots and April 28th, 2016 in the NT-RC plots, and on April 18th, 2017 in the

454 T-GM plots, and on April 19<sup>th</sup>, 2017 in the RC3 plots and May 16<sup>th</sup>, 2017 in the RC1 plots.

455 The butternut squash were manually transplanted on June 9th, 2016 and June 8th, 2017, with a

456 row spacing of 2 m and a 0.5 m plant spacing (Picture 15). The cash crop plants were fertilised

457 with commercial organic fertiliser (Dix® 9.2.2+1 MgO Italpollina). In the first year, 80 kg ha<sup>-1</sup>

N was applied with the commercial organic fertiliser on June 6<sup>th</sup>, 2016. In the second year, 72 kg ha<sup>-1</sup> N was applied with the commercial organic fertiliser on May 31<sup>st</sup>, 2017 (i.e., before soil tillage and cash crop transplantation) in the T-GM treatments, and localised in the strip-till lines on June 6<sup>th</sup>, 2017 in the NT-RC treatments. During both years, butternut squash was irrigated by drip irrigation according to crop needs.



463

464 Picture 15. View of the field trial during growth of the cash crop at the experimental organic research centrer Groupe
465 de Recherche en Agriculture Biologique (GRAB) in Avignon (FR).

In the first year, weeding operations were performed in the inter-rows of the T-GM1 and T-GM2 plots using a rototiller on June 22<sup>nd</sup>, 2016, and manual weeding was performed three times in all treatments on the 23<sup>rd</sup> of June, 12<sup>th</sup> of July and 9<sup>th</sup> of August, 2016. During the second year, manual weeding was performed twice in all treatments on the 23<sup>rd</sup> of June, and 5<sup>th</sup> of July 2017. The cash crop was manually harvested on September 7<sup>th</sup>, 2016, and September 11<sup>th</sup>, 2017. More information can be found in Navarro-Miró, Iocola, et al. (2019).

# 472 Italy (IT)

Both parallel field experiments Type A (FtA) and Type B (FtB) were newly established at the Experimental Farm of Metaponto belonging to the Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA) in southern Italy (IT) (40° 24′ N and 16° 48′ E). This location represented the Mediterranean North European climatic zone. In FtA, during the first cycle (2015–2016), the mean annual temperature was 16.7 °C and the mean annual rainfall, 539

mm, and during the second cycle (2016–2017) these environmental factors were 16.5 °C and
402 mm, respectively. In FtB, during the first cycle (2014–2015) the mean annual temperature
was 16.6 °C and the mean annual rainfall, 470 mm, and during the second cycle (2015–2016),
these environmental factors were 16.7 °C, and 539 mm, respectively. The trial soil had a clay
texture and contained on average 1.1 % organic carbon content.

In both trials, the field experiments were not repeated on the same plots in both years and were moved to an adjacent area for the second cycle. Plot size was  $6 \times 4$  m. The two ASC management strategies were: (1) roller-crimped (NT-RC) + in-line tillage to create the transplanting furrows, and (2) chopped and ploughed under and incorporated into the soil by milling (T-GM). The roller crimper was 2.25 m wide and weighed 550 kg and was designed and constructed by Soldo Macchine Agricole (Grassano, Italy) (Picture 16). In the NT-RC plots, furrows for cash crop transplanting were created by in-line tillage (Picture 16).



490

491 Picture 16. Machinery used for NT-RC management at the Experimental Farm of Metaponto belonging to the
 492 Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA) in southern Italy (IT). A tractor
 493 equipped with a roller crimper and in-line tiller.

#### 494 Experimental design

## 495 Field experiment type A

The previous crop grown in the area was fennel (*Foeniculum vulgare* Mill.). The experimental layout consisted of a split-split-plot with main plots arranged as a randomised complete block design, with three factors and three replications. The main plot was the ASC factor, and the

- 499 subplot was assigned to the ASC management strategy, and the split-plot to the fertilisation
- 500 factor (Figure 12).

501



Figure 12. The FtA experimental design at the Experimental Farm of Metaponto belonging to the Consiglio per la
Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA) in southern Italy (IT). Termination: RC - Roller
crimper + in-line tillage to create the transplanting furrows (NT-RC); and GM - ASC chopped, ploughed under and
incorporated into the soil by milling (T-GM). ASC composition: ASC0 - Control treatment maintaining the soil
without plant cover (bare soil); ASC1 - 20 % *Hordeum vulgare* + 80 % *Vicia sativa*; and ASC2 - 20% *H. vulgare* +
80 % *Vicia faba* var. *minor*. Fertilisation factor: NO - no fertiliser; CO - Commercial organic mineral fertiliser
allowed in organic farming; and AD - Anaerobic digestate from cattle residues.

The ASC species composition was: ASC1 - *Hordeum vulgare* 20 % + 80 % *Vicia sativa*, and ASC2 – *H. vulgare* 20 % + 80 % *Vicia faba* var. *minor*. The fertilisation factor consisted of: (1) no fertiliser (NO), (2) commercial organic mineral fertiliser allowed in organic farming (CO), and (3) anaerobic digestate from cattle residues (AD). The cash crop was tomato (*Solanum lycopersicum* L.).

514 Field experiment type B

The previous crop was wheat (Triticum aestivum L.). The trial had a split-plot with the main 515 plots arranged as a randomised complete block design, with two factors and three replications 516 (Figure 13). The main plot was assigned to the ASC composition and the subplot to the ASC 517 management strategy. 518



BlockI BlockII 519

520 Figure 13. The FtB experimental design at the Experimental Farm of Metaponto belonging to the Consiglio per la 521 Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA) in southern Italy (IT). Termination: RC - Roller 522 crimper + in-line tillage to create the transplanting furrows (NT-RC); and GM - ASC chopped, ploughed under and 523 incorporated into the soil by milling (T-GM). In 2015, the ASC compositions were: ASC1 - 100 % Vigna 524 unguiculata; ASC2 - 70 % V. unguiculata + 30 % Pennisetum glaucum; ASC3 - 50 % V. unguiculata + 50 % P. 525 glaucum; and ASC4 - 40 % V. unguiculata + 30 % P. glaucum + 30 % Raphanus raphanistrum subsp. sativus. In 526 2016, the ASC compositions were: ASC1 - 100 % V. unguiculata; ASC2 - 100 % Vigna radiata; ASC3 - 100 % 527 Fagopyrum esculentum; and ASC4 - 35 % V. unguiculata + 35 % V. radiata + 30 % F. esculentum. Additionally, a 528 control treatment (ASC0) maintaining the soil without plant cover (bare soil) was established.

In 2015, ASC compositions were: ASC1 - 100 % cowpea (*Vigna unguiculata* (L.) Walp.), ASC2 - 70 % cowpea + 30 % pearl millet (*Pennisetum glaucum* (L.) R.Br.), ASC3 - 50 % cowpea + 50 % pearl millet, and ASC4 - 40 % cowpea + 30 % pearl millet + 30 % radish (*Raphanus raphanistrum* subsp. *sativus* (L.) Domin). In 2016, ASC compositions were: ASC1 -100 % cowpea, ASC2 - 100 % mung bean (*Vigna radiata* (L.) R.Wilczek), ASC3 - 100 % buckwheat (*Fagopyrum esculentum* Moench), and ASC4 - 35 % cowpea + 35 % mung bean + 30 % buckwheat. The cash crop was cauliflower (*Brassica oleracea* var. *botrytis* L.).

#### 536 Agronomic management

#### 537 Field experiment type A

ASCs were sown on November 4<sup>th</sup>, 2015, and December 29<sup>th</sup>, 2016. Fertiliser was applied to 538 plots belonging to the fertilisation treatments on April 8<sup>th</sup>, 2016 and April 26<sup>th</sup>, 2017 as follows: 539 12 t ha<sup>-1</sup> of anaerobic digestate from cattle residues in the AD plots and 3.5 t ha<sup>-1</sup> of commercial 540 organic mineral fertiliser allowed in organic farming in the CO plots (Figure 12). In the T-GM 541 treatments, ASCs were chopped on April 8<sup>th</sup>, 2016 and April 26<sup>th</sup>, 2017 and ploughed under and 542 incorporated into the soil by milling on the 18th and 19th of April 2016 and April 28th, 2017. In 543 the NT-RC treatments, the ASCs were flattened by roller crimper on April 15<sup>th</sup>, 2016 and April 544 26<sup>th</sup>, 2017. The tomato crop was manually transplanted on April 28<sup>th</sup>, 2016 and May 5<sup>th</sup>, 2017, 545 with a row spacing of 1 m and a 0.40 m plant spacing (Picture 17). In the NT-RC system, ASC 546 re-growth was mowed twice on May 10<sup>th</sup>, and 23<sup>rd</sup>, 2016. No further weed management was 547 548 carried out during growth of the cash crop, whereas in the second year, inter-row weed control 549 by mowing was carried out on the 12<sup>th</sup> of July 2017. The cash crop was drip irrigated weekly. The cash crop harvest was performed from July 7th to August 25th, 2016, and from July 18th to 550 August 25<sup>th</sup>, 2017. 551



552

Ficture 17. View of the FtA trial during growth of the cash crop at the Experimental Farm of Metaponto belonging to
the Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA) in southern Italy (IT).

#### 555 Field experiment type B

ASCs were sown on April 21<sup>st</sup>, 2015 and April 19<sup>th</sup>, 2016, and were irrigated on emergence. Commercial organic fertiliser (150 kg ha<sup>-1</sup> N, 450 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub>, and 150 kg ha<sup>-1</sup> K<sub>2</sub>O) was applied just before the ASC termination, whereas in the second year, fertiliser was applied during cash crop development. ASC management was carried out on July 29<sup>th</sup>, 2015, whereas in the second year, the ASC was terminated by T-GM on July 27<sup>th</sup>, 2016, and by NT-RC on July 28<sup>th</sup>, 2016.

The cauliflower crop was transplanted on August 3<sup>rd</sup> in both years, with a row spacing of 1.0 m and a 0.45 m plant spacing. During the first year, the NT-RC plots were mowed every two weeks to reduce ASC regrowth biomass, whereas only two weeding operations were carried out in the T-GM plots. During the second year, only two ASC regrowth mowing operations were required, whereas no weed control was carried out in the T-GM plots. The cash crop was irrigated by micro-sprinklers according to crop requirements. The cash crop harvest was performed from November 23<sup>rd</sup> to December 15<sup>th</sup>, 2015, and November 28<sup>th</sup>, 2016.

569 More information about this trial can be found in Navarro-Miró et al. (2017), Navarro-Miró,

570 Iocola, et al. (2019) and Navarro-Miró, Blanco-Moreno, et al. (2019).

## 571 Slovenia (SI)

#### 572 Field experiment type A

## 573 Experimental design

The field trial was newly established at the University of Maribor (Pivola), Faculty of Agriculture and Life Sciences (UM), Slovenia (SI) (46° 30' N and 15° 37' E). This trial represented the Alpine South European climatic zone. During the first cycle (2015–2016), the mean annual temperature was 10.9 °C and the mean annual rainfall, 1,009 mm, and during the second cycle (2016–2017) these environmental factors were 11.1 °C and 961 mm, respectively. The trial soil had a loam texture with an average 2.66 % organic carbon content. The experiment was not repeated in the same plots in both years, and was moved to an adjacent

area for the 2016–2017 cycle. The previous crop grown in the area was barley. The trial had a

split-split-plot design with plots arranged in a randomised complete block design, with three

583 factors and four repetitions (Figure 14).



Figure 14. Experimental design of the trial established at the University of Maribor (Pivola), Faculty of Agriculture and Life Sciences (UM), Slovenia (SI). ASC compositions were: ASC1 (green) - 100 % *Hordeum vulgare*; and ASC2 (red) - 100 % *Trifolium incarnatum*; and two different controls: 1) No ASC (white) and 2) Black foil (grey). The two ASC termination strategies were: RC - ASC terminated with a roller crimper + in-line tillage (NT-RC); and GM - ASC mulched and incorporated into the soil and seedbed prepared with a rotary harrow (T-GM). Fertilisation factor: M - Application of livestock manure (30 t ha<sup>-1</sup>) before sowing ASC; and O - Without manure application.

The ASC species composition was: 100 % Hordeum vulgare (220 kg ha<sup>-1</sup>), ASC2: - 100 % 584 Trifolium incarnatum L. (35 kg ha<sup>-1</sup>), and two different controls: (1) no ASC and (2) black foil. 585 The two ASC termination strategies were: (1) cover crop terminated with a roller crimper + in-586 line tillage (NT-RC), and (2) ASC mulched and incorporated into the soil and seedbed prepared 587 with a rotary harrow (T-GM). The roller crimper was 2.5 m wide and weighed 700 kg and was 588 created through co-operation between the Faculty of Agriculture and Life Sciences, Department 589 of Organic Agriculture, Crops, Vegetables and Ornamental Plants and Gorenc d.o.o. from 590 Spodnji Brnik in Slovenia (Picture 18). In the NT-RC plots, furrows for cash crop transplanting 591 were created by in-line tillage (Picture 18). The fertilisation factor had two levels: M application 592

- 593 of livestock manure (30 t ha<sup>-1</sup>) before sowing the ASCs, and O no manure application. Plot
- size was  $2.5 \times 2.5$  m. The cash crop was cauliflower (*Brassica oleracea* var. *botrytis* L.).



595

596 Picture 188. Machinery used for NT-RC management in the trial established at the University of Maribor (Pivola),
 597 Faculty of Agriculture and Life Sciences (UM), Slovenia (SI). A tractor equipped with a roller crimper and in-line
 598 tiller.

## 599 Agronomic management

The fertilisation treatment was performed using livestock manure (30 t ha<sup>-1</sup>) on August 27<sup>th</sup>, 2015 and on August 24<sup>th</sup>, 2016. ASC1 was sown on August 31<sup>st</sup>, 2015 and on August 25<sup>th</sup>, 2016, whereas ASC2 was sown on October 26<sup>th</sup>, 2015 and October 25<sup>th</sup>, 2016. The ASCs were managed in the T-GM plots on May 19<sup>th</sup>, 2016 and on May 20<sup>th</sup>, 2016 in the NT-RC plots. During the second cycle, all plots were managed on May 18<sup>th</sup>, 2017.

The cauliflower crop was transplanted on June 3<sup>rd</sup>, 2016, and May 24<sup>th</sup>, 2017 with a row spacing 605 of 0.6 m and a 0.40 m plant spacing (Picture 19). During the cash crop cycle, all plots were 606 fertilised using commercial organic fertilisers when the cash crop was transplanted 607 (70 kg ha<sup>-1</sup> N), and during cash crop development (70 kg ha<sup>-1</sup> N). During the second year, the 608 cash crop was irrigated twice using micro-sprinklers. Weed management was performed 609 manually in all treatments. During the first cycle, three weeding operations were carried out in 610 the T-GM and control plots on June 29th, 2016, July 19th, 2016, and August 11th, 2016. In the 611 NT-RC plots, only one operation was required (August 12<sup>th</sup>, 2016). During the second cycle, 612 four weeding operations were carried out in the T-GM and control plots (June 19th, 2017, July 613

- 5<sup>th</sup>, 2017, July 26<sup>th</sup>, 2017, and August 17<sup>th</sup>, 2017), whereas in the NT-RC plots, two operations
- 615 were required (July 5<sup>th</sup>, 2017 and August 9<sup>th</sup>, 2017). The cash crop harvest was performed on
- 616 September 29<sup>th</sup>, 2016 and September 5<sup>th</sup>, 2017.



617

618 Picture 19. The cauliflower cash crop in the trial was established at the University of Maribor (Pivola), Faculty of
619 Agriculture and Life Sciences (UM), Slovenia (SI).

620 More information can be found in Bavec, Robačer, Bavec, et al. (2017), Bavec, Robačer, Lisec,

et al. (2017) and Navarro-Miró, Blanco-Moreno, et al. (2019).

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674

1 Appendix S2. Details of sampling procedures for Carabidae, Staphylinidae and Araneae, N

2 leaching, beta-glucosidase, marketable yield and cash crop quality carried out in each trial.

3

# 4 1. Carabidae, Staphylinidae and Araneae trapping methodology

5 The activity densities of the Carabidae, Staphylinidae and Araneae were assessed using pit-fall6 traps.

7

## 8 Belgium - Research Institute for Agriculture, Fisheries and Food (BE-ILVO)

# 9 Field experiment type A

10 The pit-fall traps were placed in the middle of each sub-plot to avoid interference between 11 treatments. Pit-fall traps contained diluted formaldehyde. All traps were emptied every two 12 weeks over a five-month period, starting two weeks after the cabbage was planted and 13 continuing until just before harvesting. After collection, arthropods were conserved in alcohol in 14 the laboratory at room temperature until determination.

# 15 Denmark (DK)

# 16 Field experiment type A

The pit-fall station consisted of two pit-fall traps connected with a 10-cm-wide and 1-m- long metal barrier. In both years, two sampling periods (from August–October) of 14 days each were carried out. Pit-fall traps were filled with propylenglycol (40 %). After collection, biological material was rinsed and stored in 70 % alcohol until determination.

### 21 Italy (IT)

# 22 Field experiment type A and type B

23 Each trap consisted of two collecting cups (600 mL; 10-cm diameter) connected by a 10-cm-

high and 1-m-long Plexiglas barrier. Cups were filled with 40 % aqueous solution of propylene

25 glycol as a killing and preservative agent.

26 In FtA, traps were active for seven out of 21 days from early June to late July in 2016 and 2017.

27 Trapped arthropods were collected four times.

In FtB, traps were continuously active for the whole growing season, i.e. from early September to the end of December in 2015 and 2016. Traps were checked every three weeks and arthropods were collected four times.

31 Slovenia (SI)

## 32 Field experiment type A

The pit-fall station consisted of two pit-fall traps connected by a 10-cm-wide and 1-m- long metal barrier. In the first year, five sampling periods (end of June to end of August) of two weeks each were performed. In the second year, there were six sampling periods (beginning of June to end of August) of two weeks each with the exception of the first sampling after 15 days. Pit-fall traps were filled with propylenglycol (40 %). After collection, biological material was rinsed and stored in 70 % alcohol and checked and identified in the laboratory.

39 Spain (ES)

#### 40 Field experiment type B

In Spain, we only studied the activity density of spiders in the FtB trial. The pit-fall station consisted of two pit-fall traps connected by a 10-cm-wide and 1-m-long plexiglas barrier. In the first year, eight sampling periods (from August to December) of 13–18 days each were carried out. In the second year, we carried out seven sampling periods (from September to December) of 12–22 days. Pit-fall traps were filled with propylenglycol (40 %). After collection, biological material was rinsed and stored in 70 % alcohol and checked and identified in the laboratory.

47

# 48 **2. Beta-glucosidase**

49 The effect of the ASC management on soil quality was assessed using beta-glucosidase enzyme50 activity as an indicator.

51

### 52 Belgium - INAGRO (BE-INAGRO)

#### 53 Field experiment type A

54 The activity of beta-glucosidase was assessed using the method described in Alef and 55 Nannipieri, (1995). In short, 4 ml of modified universal buffer (pH 6.0) and 1 ml of 25 mM pnitrophenyl-β-D-glucospyranoside solution was added to one gram of the pre-incubated moist 56 soil. The soil suspensions were incubated for 1 h at 37 °C. After incubation, 1 ml of CaCl<sub>2</sub> and 4 57 58 ml of Tris buffer (pH 12.0) were added. If needed, soil suspensions were diluted twice with Tris 59 buffer (pH 10.0) to make the filtrates fit the range of the p-nitrophenol standard series. The 60 colour intensity of the filtrates and standard series was measured at 400 nm with a Cary 50 UV-61 Visible spectrophotometer (Varian Inc., Palo Alto, United States).

### 62 **Denmark (DK)**

# 63 Field experiment type A

64 Beta-glucosidase activity was measured by adding 1 ml of 25 mM p-nitrophenyl-β-D-glucoside solution and 4 ml of modified universal buffer to two technical replicates of 1 g of sieved soil 65 66 (fresh weight). The samples were incubated at 37 °C for 1 h. P-nitrophenyl-β-D-glucoside 67 solution was added to the control samples after incubation. Subsequently, 1 ml of 0.5 M CaCl<sub>2</sub> 68 and 4 ml of Tris-buffer pH 12 were added to the samples, which were then filtered immediately 69 using Whatman n°. 5 papers. Released p-nitrophenol in the extract was determined by 70 measurement of the optical density with a Varian Cary 50 spectrophotometer at 400 nm. Beta-71 glucosidase activity was determined as the difference between experimental and control 72 samples.

73 Italy (IT)

# 74 Field experiment type A

75 The activity of beta-glucosidase was determined by a heteromolecular exchange procedure76 described by Fornasier and Margon (2007).

77

### 78 **3.** N leaching

- 79 The nitrogen leaching potential (N leaching) was measured using as an indicator the soil mineral
- 80 nitrogen at harvest of the cash crop (Hutchings & Kristensen, 1995).
- 81

## 82 Belgium - Walloon Agricultural Research Center (BE-CRA-W)

# 83 Field experiment type A

The mineral nitrogen content was assessed using a soil depth of 0.3 m because the dry weather did not allow us to sample more deeply. Six samples were collected per plot area and mixed into one composite sample. Soil mineral nitrogen, measured when the cash crop was harvested, was extracted by 0.5 M KCl (1:5, w/v) and measured by continual flow colourimetry according to QuickChem® Method 12-107-06-3-B and QuickChem® Method 12-107-04-1-B for NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N, respectively.

# 90 Belgium - INAGRO (BE-INAGRO)

# 91 Field experiment type A

Soils were sampled with a hand-driven auger with a 13-mm inner diameter to depths of 0–0.3 m, 0.3–0.6 m and 0.6–0.9 m. Four subsamples were taken per plot and combined into one composite sample per soil layer. Soil  $N_{min}$  was determined by the extraction of nitrate and ammonium in 1-M KCl for 1 h and by analysis of the supernatant using standard colourimetry.

## 96 Denmark (DK)

# 97 Field experiment type A

Soil samples for N leaching were taken to a depth of 2.5 m in November. Ten sub-samples were randomly taken in each subplot by a machine-driven soil piston auger with a 14-mm innerdiameter at depths of 0–0.25 m, 0.25–0.5 m, 0.5–1 m, 1–1.5 m, 1.5–2 m and 2–2.5 m and then mixed into a composite sample for each depth. Soil samples were frozen until mineral N analysis. After thawing, the subsamples (each 100 g fresh weight) were extracted in 1-M KCl for 1 h (1 soil: 2 solution). The soil extract was centrifuged and the supernatant was subjected to 104  $NH_4^+$  and  $NO_3^-$  analyses using standard colorimetric methods with an AutoAnalyzer 3 105 (Bran+Luebbe, Germany).

106 Estonia (EE)

## 107 Field experiment type A

108 For soil mineral nitrogen, measured when the cash crops were harvested, four subsamples were

109 taken per plot and mixed into one composite sample. Soil  $N_{min}$  was determined by the extraction

110 of nitrate and ammonium in 2-M KCl (1:10, w/v) for 1 h and by analysis of the supernatant

- 111 using standard colourimetry. The analysis of the supernatant was performed twice to control for
- 112 intra-laboratory variability.

113 Italy (IT)

# 114 Field experiment type A

Soil mineral nitrogen, measured when the cash crop was harvested, was extracted in 2-M KCl (1:10, w/v) and measured using continual flow colourimetry according to Krom (1980) and Henriksen and Selmer-Olsen (1970) for  $NH_4^+$ -N and  $NO_3^-$ -N, respectively. All the soil laboratory tests were carried out in triplicate to control for intra-laboratory variability.

119

### 120 4. Marketable yield

121 The indicator of the cash crop marketable yield was assessed using the dry biomass of the122 marketable yield of the cash crop.

123

#### 124 Belgium - Walloon Agricultural Research Center (BE-CRA-W)

## 125 Field experiment type A

126 The cabbage marketable yield was estimated on two days (October 25th and 26th, 2017) by

127 evaluating 21 cabbages per plot selected in the centre of the plot along three central lines. The

- 128 marketable heads was assessed by measuring the dry matter (t ha<sup>-1</sup>; 60 °C until constant weight).
- 129 The minimum diameter of the cabbage head considered as marketable was 130 mm.

130	Belgium - INAGRO (BE-INAGRO)
131	Field experiment type A
132	Cabbage yield at harvest was obtained by hand-harvesting two rows $\times$ 2 m. Plant samples were
133	divided into marketable yield; crop residues and fresh and dry weights were calculated.
134	Denmark (DK)
135	Field experiment type A
136	Cabbage marketable yield was assessed by harvesting 16–18 plants (two crop rows $\times$ 4.5 m) per
137	plot at harvest (October).
138	Estonia (EE)
139	Field experiment type A
140	In both years, we estimated the cabbage marketable yield by sampling five randomly chosen
141	plants per plot.
142	Spain (ES)
143	Field experiment type A
144	In the first year, we estimated the pepper marketable yield by analysing eight random plants per
145	plot during twelve weekly samplings. In the second year, we assessed five random plants per
146	plot during five biweekly samplings. In both years, we calculated the accumulated yield per
147	plot.
148	Field experiment type B
149	In both years, we estimated the cabbage marketable yield by assessing five randomly chosen
150	plants per plot.
151	France (FR)
152	Field experiment type A
153	In both years, we measured the yields of 10 plants per plot $\times$ 4 plots per treatment.
154	Italy (IT)

155 Field experiment type A

At harvest, in the first year, tomatoes were collected from three randomly selected plants (in the centre of the rows in each elementary plot) at three different times in July and August 2016, and marketable and total yields (t ha<sup>-1</sup>) were recorded. In the second year, tomatoes were collected from three different plants at four different times in July and August 2017, and marketable and total yields (t ha<sup>-1</sup>) were recorded.

## 161 Field experiment type B

At harvest, in both years, cauliflower heads were collected from three randomly selected plants
(in the centre of the rows in each elementary plot), and marketable and total yields (t ha<sup>-1</sup>) were
calculated.

165

### 166 5. Cash crop quality

167 The cash crop quality indicator included different measurements of the marketable parameters168 of the cash crop depending on the crop and trial.

169

### 170 Belgium - Walloon Agricultural Research Center (BE-CRA-W)

### 171 Field experiment type A

172 To assess the marketable yield, the cash crop quality was estimated measuring the head

173 diameter (mm) of 21 cabbages collected from the centre of the selected plot. The minimum head

- 174 diameter considered as marketable was 130 mm.
- 175 Estonia (EE)

## 176 Field experiment type A

177 In both years, cabbage quality was assessed by measuring the head diameter of five randomly

- 178 chosen plants per plot.
- 179 **Spain (ES)**
- 180 Field experiment type A

181	In the first year, we estimated the cash crop quality by measuring the length of each pepper
182	when harvesting of eight random plants per plot in twelve weekly samplings. In the second year,
183	we used the same procedure, except that we chose five plants at random per plot and five
184	biweekly samplings.
185	Field experiment type B
186	In both years, cabbage quality was assessed by measuring the head diameter of five randomly

- 187 chosen plants per plot.
- 188 France (FR)

# 189 Field experiment type A

190 The cash crop quality of butternut squash was measured by calculating the average weight of

191 the fruit.

192 Italy (IT)

## 193 Field experiment type A

194 At harvest, in both years, tomato quality was assessed by measuring the total soluble solids

- 195 (refractometric index, °Brix) of the fruits.
- 196 Field experiment type B
- 197 At harvest, in both years, cauliflower head quality was assessed by measuring the dry matter
- 198 weight (t ha<sup>-1</sup>; 70 °C until constant weight) of marketable heads.

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1 Appendix S3. Minimum and maximum value of each variable in each trial.

2 This Appendix shows the minimum and maximum value of each variable in each trial. Our study compared the no-till roller crimping (NT-RC) and tilling as green manure (T-

3 GM) of agroecological service crop (ASC) management strategies. We combined results from 11 organic arable vegetable field trials located in Belgium (BE), Denmark (DK),

4 Estonia (EE), France (FR), Italy (IT), Slovenia (SI), and Spain (ES). In BE, three different trials were set up across the country (BE-ILVO, BE INAGRO, and BE-CRA-W). Two

5 parallel field experiment types were carried out: FtA - Spring-summer cash crop and FtB- Autumn-winter cash crop.

			Ecological indicators			Environmental indicators			Agronomic indicators			
Country	Trial	Termination	Carabidae AD	Staphylinidae AD	Araneae AD	PRE-EUE	N leaching	Beta-glucosidase	Weed density	Marketable yield	Cash crop quality	M-EUE
DE CDA W	FtA	T-GM					4.8 - 8.2		1 - 4	0 - 0.9	59.5 - 144.3	
BE-CRA-W		NT-RC					5.1 - 9		0 - 5	0 - 0	40.8 - 109	
BE-ILVO	FtA	T-GM	2.2 - 9	0.1 - 1.4		0.03 - 0.03						0.54 - 1.22
		NT-RC	1.8 - 14.2	0.2 - 1.3		0.05 - 0.08						0 - 0.54
BE-INAGRO	FtA	T-GM					7.7 - 27.8	67 - 236.4		3.4 - 5.4		
		NT-RC					6.4 - 32.6	75.9 - 186.3		0 - 4.3		
DK	FtA	T-GM	0.3 - 41.5	0 - 4.5		0.05 - 0.14	5.1 - 20.9	86.5 - 116.9	309 - 1498	0 - 6.6		0 - 2.56
DR		NT-RC	6.3 - 55.5	0 - 2.5		0.04 - 0.14	7.4 - 21.9	77.1 - 123.9	89 - 665	0 - 6.1		0 - 2.49
EE	FtA	T-GM				0.04 - 0.16	8.6 - 19.5		108 - 341	0 - 1.1	582.6 - 777.9	0 - 0.58
EE		NT-RC				0.06 - 0.14	5.8 - 22.5		31 - 101	0 - 0.5	461.6 - 765.2	0 - 0.22
	FtA	T-GM				0.13 - 0.18			95 - 1090	2.2 - 3.7	17.1 - 20	0.7 - 1.05
ES		NT-RC				0.1 - 0.21			0 - 605	2.5 - 4.2	15 - 22	0.81 - 1.31
	S FtB	T-GM			10.8 - 23.6	0.04 - 0.14			110 - 1440	0.3 - 3.5	5 - 18.2	0.07 - 0.96
		NT-RC			10.8 - 31.8	0.05 - 0.18			10 - 2585	0 - 3.5	6.5 - 17.6	0 - 0.81
FR	FtA	T-GM				0.06 - 0.12			44 - 1078	2.9 - 5.3	1 - 1.5	1.19 - 2.32
		NT-RC				0.08 - 0.16			8.5 - 164	1.3 - 3.2	0.9 - 1.3	0.65 - 1.68
	FtA	T-GM	0 - 12.7	0 - 3.7	0 - 52.2	0.04 - 0.14	0.5 - 44.4	0.9 - 4.6	4 - 124	0.6 - 5.5	3.6 - 6	0.18 - 2.48
IT		NT-RC	0 - 25.2	0 - 5.2	0.7 - 22.5	0.04 - 0.13	2.4 - 36.9	1.4 - 4.9	4 - 146	1 - 10.9	3.8 - 5.8	0.48 - 3.91
11	FtB	T-GM	2.1 - 42.7	0.7 - 14.9	3 - 20.7	0.06 - 0.17			24 - 220	0.3 - 1.9	7.4 - 13.7	0.17 - 1.06
		NT-RC	18.3 - 45.3	0.7 - 23.4	3.8 - 23.8	0.05 - 0.15			64 - 339.2	0 - 1.5	6.7 - 14.8	0 - 0.96
SI	FtA	T-GM	8.9 - 91.9	0.3 - 10	20.3 - 55				74 - 880			
		NT-RC	7 - 42.9	0.1 - 8.8	10.9 - 43.1				16 - 352			

6 Ecological indicators (Carabidae AD, Staphylinidae AD, Araneae AD) (individuals per 7 days); Environmental indicators: PRE-EUE: energy-use efficiency using the potentially recyclable

7 energy as the output of the cropping system; N leaching: nitrogen leaching potential (BE-CRA-W: kg N ha<sup>-1</sup>; BE-INAGRO, DK, EE and IT: mg N kg<sup>-1</sup>); Beta-glucosidase (BE-INAGRO and

- DK:  $\mu$ g PNP g<sup>-1</sup> h<sup>-1</sup>; IT: nmol 4-MUF g<sup>-1</sup> h<sup>-1</sup>). Agronomic indicators: Weed density (individuals m<sup>-2</sup>); Marketable yield (t ha<sup>-1</sup>); Cash crop quality (cash crop quality indicator included different measurements of the cash crop's marketable parameters, given in Appendix 2); M-EUE: Energy-use efficiency using the marketable yield as the output of the cropping system. 8
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