The concurrent assessment of agronomic, ecological and environmental variables enables better choice of agroecological service crop termination management

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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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Abstract

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

2. We evaluated effects of the ASC management strategies: no-till roller crimping (NT-RC) and green manuring (T-GM) on cropping system performance using agronomic, environmental, and ecological indicators, to exemplify the need for multidimensional analysis to understand management implications for addressing environmental and agronomic challenges. We combined the results from eleven organic vegetable field trials conducted in seven European countries over a period of two years to test for general trends.

3. Our results provide solid evidence that NT-RC management across different pedo-climatic conditions in Europe enhances the activity density of ground and rove beetles, and improves both the potential energy recycling within the system and weed control. However, in NT-RC plots lower cash crop yield and quality, energetic efficiency of production, and activity density of spiders was 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, our study also indicates a need for agronomic and environmental improvements while promoting a wider acceptance of this strategy.

Key words

1. Introduction

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

85 that reduce productivity (e.g., pest damage), generate environmental issues (e.g., nutrient leaching), and

86 affect both the maintenance and functioning of ecosystems and human well-being (Power, 2010; Zhang,

87 Ricketts, Kremen, Carney, & Swinton, 2007).

88 In Europe, 1.9 % of arable land (2.2 million ha) is devoted to vegetable crops and produces

89 approximately 65 million tonnes of fresh vegetables (De Cicco, 2016; EUROSTAT, 2019). Vegetables

90 are the crops that need the highest energy input (Elsoragaby, Yahya, Mahadi, Nawi, & Mairghany, 2019)

91 and, to ensure yields, vegetable production currently requires the greatest agrochemical input (i.e.,

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

93 of these crops has caused environmental problems, including the notable consumption of non-renewable

94 resources and nutrient leaching (Min, Zhang, & Shi, 2012; Torrellas et al., 2012) as well as health

95 concerns derived from the presence of pesticide residues (González-Rodríguez, Rial-Otero, Cancho-

96 Grande, & Simal-Gándara, 2008).

97 Organic farming was originally promoted as a holistic farming system aimed at improving soil health,

98 and environmental and social aspects of agricultural production (Seufert, Ramankutty, & Mayerhofer,

99 2017). In recent decades, its conventionalisation has led to the intensification and specialisation of

100 organic production (Buck, Getz, & Guthman, 1997; Darnhofer, Lindenthal, Bartel-Kratochvil, &

101 Zollitsch, 2010), and several studies have questioned the environmental benefits and agronomic

102 viability of organic farming (Seufert et al., 2017; Trewavas, 2001, 2004; Tuomisto, Hodge, Riordan, &

103 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

120   farming systems (Ponisio et al., 2015). Some studies argue that organic farming is less efficient as it

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

131 natural water bodies (Trewavas, 2001). On the other hand, Trewavas (2004) highlighted the fact that

132 recycling energy and nutrients within the cropping system cannot compensate for the absorption of

133 nutrients by the cash crop. Therefore, this type of management can lead to a progressive depletion of

134 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,

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).

171   In this study, we analysed effects of the ASC management strategies (NT-RC vs. T-GM) on organic

172   vegetable cropping system performance by means of agronomic, environmental, and ecological

173   indicators, in different vegetable crops, soils and climatic conditions across Europe. We compared NT-

174   RC and T-GM using a system comparison approach to exemplify the need for multidimensional analysis

175   to address some of the most frequent criticisms and constraints as mentioned above. We also aimed to

176   show the importance of an appraisal of the environmental and ecological implications—as well as the

177   agronomic benefits to the agroecosystem—under different crop, soil, and climatic conditions to evaluate

178   the pros and cons of the different management systems before promoting them to organic vegetable

179   farmers, advisors, and policymakers. To this end, we combined results obtained over a two year period

180   from eleven organic vegetable field trials located in seven European countries as part of the SoilVeg

181   project (ERA-Net CORE Organic Plus).

182

2. Material and methods

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2.1. Locations and field trials

184

185   We combined results from 11 organic arable vegetable field trials located in Belgium (BE), Denmark

186   (DK), Estonia (EE), France (FR), Italy (IT), Slovenia (SI), and Spain (ES). In BE, three different trials

187   were set up across the country (BE-ILVO, BE-INAGRO, and BE-CRA-W). These vegetable production

188   trials were located in different climatic zones (Metzger, Bunce, Jongman, Mücher, & Watkins, 2005)

189   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

199 trial for both experiment types. In total, results from twenty-two original datasets were analysed (i.e.,

200 from 11 field experiments carried out over two years) (Table 1).

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

2.3. Cropping system performance indicators

215 We used a set of ecological, environmental, and agronomic indicators with a system comparison

216 approach to compare the performance of NT-RC and T-GM. In addition to a set of common indicators

217 evaluated in all experiments, we selected a number of tailored indicators which were used according to

218 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    $AD = \frac{n}{T} \cdot \frac{7}{d}$

235   where n is the total abundance of each taxon, T is the number of traps, and d is the number of days that

236   traps were operative.

237   The effect of the ASC management strategy on soil quality was assessed using beta-glucosidase enzyme

238   activity. This enzyme has known sensitivity to soil tillage, irrespective of pedo-climatic conditions, and

239   can, therefore, provide rapid information regarding changes in soil properties (Ekenler & Tabatabai,

240   2003; Knight & Dick, 2004). In BE-INAGRO and DK beta-glucosidase was assessed using the method

241   described in Alef and Nannipieri (1995), while in IT was determined by the procedure described by

242   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).

259   Further details of beta-glucosidase enzyme activity determination and the assessment of soil mineral

260   nitrogen at harvest of the cash crop are provided in Appendix S2.

261
262   2.3.2. Agronomic indicators

263   We evaluated the effects of the ASC management strategies on two indicators: the cash crop marketable

264   yield, and the cash crop quality. The cash crop marketable yield indicator was assessed using the dry

265   biomass of the marketable cash crop yield, whereas the cash crop quality indicator included different

266   measurements of the cash crop marketable parameters, specific to each crop (cabbages - head diameter;

267   pepper - fruit length; butternut squash - fruit weight; tomato - fruit total soluble solids with

268   refractometric index, °Brix; cauliflower - marketable head dry matter weight), as indicated in Appendix

269   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^{-2}). 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**

281   Each trial was conducted under its own particular pedo-climatic conditions and experimental design.

282   Thus, instead of pooling the raw data from all the different trials, we fitted a statistical model for each

283   trial and indicator. We used a meta-analytic approach to combine the *P*-values and assess the effect of

284   the ASC management strategies on each indicator for all the trials. This approach is known to be almost

285   as powerful as approaches based on data combination (Zaykin, 2011).

286   Statistical models for each partner were fitted according to the experimental variables evaluated and the

287   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

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

310   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

311   selected for the study; and Φ and Φ^{-1} are are the standard normal cumulative distribution function

312   and its inverse, respectively. For this study, we weighted *Zi* using the standardised effect size:

313     $w_i = \dfrac{|\mu_i|}{SE_i}$

314   where μ_i is the coefficient estimate, and *SE_i* is its standard error. To test for the same alternative

315   hypothesis, individual *P*-values were converted to one-sided values before combining as follows:

316     $p_{one-sided} = \begin{cases} \dfrac{p_{two-sided}}{2}, & \text{if the direction of the effect coincides with the alternative hypothesis} \\ 1-\dfrac{p_{two-sided}}{2}, & \text{otherwise.} \end{cases}$

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

323   The statistical analysis showed that the ASC management strategy significantly affected soil arthropod

324   AD and PRE-EUE (Figure 1), whereas it had no significant effect on the beta glucosidase indicators or

325   N-leaching across the trials, except for the BE-CRA-W trial where the N leaching potential was

326   significantly affected (Table 2).

327   According to the weighted Stouffer's test, the Carabidae AD was significantly higher under NT-RC

328   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

331 Staphylinidae AD under NT-RC in IT-FtA and IT-FtB whereas in BE-ILVO-FtA and SI-FtA, the

332 Staphylinidae AD was significantly lower (Table 2). Spider AD was lower under NT-RC than T-GM

333 across the trials (Figure 1), but only significantly so in two out of the five evaluated trials (Table 2).

334 The energy recycling efficiency of the ASC management strategies (evaluated using the PRE-EUE

335 indicator) was significantly higher across trials under NT-RC compared to T-GM (Figure 1). The PRE-

336 EUE was significantly higher under NT-RC in four out of eight trials, and was significantly lower only

337 in IT-FtB (Table 2).

338 The ranges (i.e., maximum and minimum) of the environmental and ecological indicators for each trial

339 are presented in Appendix S3.

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 in

350 Appendix S3.

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.

363 The overall results indicate that, in spite of some differences between trials, NT-RC enhanced weed

364 control in the early growing season, and the AD of ground and rove beetles as well as the potential

365 recycling of energy within the system when compared to T-GM. However, compared to T-GM, NT-RC

366 lowered cash crop yield and quality, the energetic efficiency of production, and the AD of spiders in

367 the vegetable crops and under the different soil and climatic conditions in the representative European

368 countries.

369 The consistent effectiveness of NT-RC on reducing weed density across countries validates this

370 approach as an effective strategy for European organic farmers to manage weeds during the early stages

371 of vegetable growth. It is worth noting that other studies on the reduction of tillage intensity in organic

372 farming analysed the effect of both ASC management strategies on weed density, weed species richness,

373 and community composition (Navarro-Miró, Blanco-Moreno, et al., 2019). Implementation of NT-RC

374 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).

386   In our study, spider AD was lower under NT-RC compared to T-GM across trials. This finding

387   contradicts a growing body of work indicating the positive effects on spider abundance of straw mulch

388   (Sunderland & Samu, 2000), and of conservation tillage (Tamburini et al., 2016). The lack of a clear

389   pattern between ASC termination strategy and spider populations calls for further studies to improve

390   knowledge of how flattened mulch may affect macrofauna based on body size, movement, behaviour,

391   guild, and dispersal methods (Baatrup, Rasmussen, & Toft, 2018; Cardoso, Pekár, Jocqué, &

392   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 beta-

421   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

438   different climatic conditions in Europe. However, compared to T-GM, NT-RC affects negatively some

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 NT-

445 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

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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

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467
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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.

475   **References**

476   Alef, K., & Nannipieri, P. (1995). Methods in Applied Soil Microbiology and Biochemistry (A.

477   P. London, Ed.). doi: 10.1016/B978-0-12-513840-6.X5014-9

478   Alluvione, F., Moretti, B., Sacco, D., & Grignani, C. (2011). EUE (energy use efficiency) of

479   cropping   systems   for   a   sustainable   agriculture.   *Energy*,   *36*(7),   4468–4481.   doi:

480   10.1016/J.ENERGY.2011.03.075

481   Altieri, M. A., Lana, M. A., Bittencourt, H. V, Kieling, A. S., Comin, J. J., & Lovato, P. E. (2011).

482   Enhancing Crop Productivity via Weed Suppression in Organic No-Till Cropping Systems in

483   Santa   Catarina,   Brazil.   *Journal   of   Sustainable   Agriculture*,   *35*,   855–869.   doi:

484   10.1080/10440046.2011.588998

485 Baatrup, E., Rasmussen, A. O., & Toft, S. (2018). Spontaneous movement behaviour in spiders

486 (Araneae) with different hunting strategies. *Biological Journal of the Linnean Society*, *125*(1),

487 184–193. doi: 10.1093/BIOLINNEAN/BLY099

488 Barut, Z. B., Ertekin, C., & Karaagac, H. A. (2011). Tillage effects on energy use for corn silage

489 in   Mediterranean   Coastal   of   Turkey.   *Energy*,   *36*(9),   5466–5475.   doi:

490 10.1016/J.ENERGY.2011.07.035

491 Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models

492 Using {lme4}. *Journal of Statistical Software*, *67*(1), 1--48. doi: 10.18637/jss.v067.i01

493 Buck, D., Getz, C., & Guthman, J. (1997). From Farm to Table: The Organic Vegetable

494 Commodity Chain of Northern California. *Sociologia Ruralis*, *37*(1), 3–20. doi: 10.1111/1467-

495 9523.00033

496 Canali, S., Campanelli, G., Ciaccia, C., Leteo, F., Testani, E., & Montemurro, F. (2013).

497 Conservation tillage strategy based on the roller crimper technology for weed control in

498 Mediterranean vegetable organic cropping systems. *European Journal of Agronomy*, *50*, 11–18.

499 doi: 10.1016/J.EJA.2013.05.001

500 Canali, S., Diacono, M., Campanelli, G., & Montemurro, F. (2015). Organic No-Till with Roller

501 Crimpers: Agro-ecosystem Services and Applications in Organic Mediterranean Vegetable

502 Productions. *Sustainable Agriculture Research*, *4*(3), 70. doi: 10.5539/sar.v4n3p70

503 Cardoso, P., Pekár, S., Jocqué, R., & Coddington, J. A. (2011). Global Patterns of Guild

504 Composition   and   Functional   Diversity   of   Spiders.   *PLoS ONE*,   *6*(6),   e21710.   doi:

505 10.1371/journal.pone.0021710

506 Carr, P. M., Gramig, G., & Liebig, M. (2013). Impacts of Organic Zero Tillage Systems on Crops,

507 Weeds, and Soil Quality. *Sustainability*, *5*(7), 3172–3201. doi: 10.3390/su5073172

508   Casagrande, M., Peigné, J., Payet, V., Mäder, P., Sans, F. X., Blanco-Moreno, J. M., … David, C.

509   (2016). Organic farmers' motivations and challenges for adopting conservation agriculture in

510   Europe. *Organic Agriculture*, *6*(4), 281–295. doi: 10.1007/s13165-015-0136-0

511   Ciaccia, C., Canali, S., Campanelli, G., Testani, E., Montemurro, F., Leteo, F., & Delate, K. (2016).

512   Effect of roller-crimper technology on weed management in organic zucchini production in a

513   Mediterranean climate zone. *Renewable Agriculture and Food Systems*, *31*(02), 111–121. doi:

514   10.1017/S1742170515000046

515   Ciaccia, C., Montemurro, F., Campanelli, G., Diacono, M., Fiore, A., & Canali, S. (2015). Legume

516   cover crop management and organic amendments application: Effects on organic zucchini

517   performance   and   weed   competition.   *Scientia   Horticulturae*,   *185*,   48–58.   doi:

518   10.1016/J.SCIENTA.2015.01.011

519   Ciaccia, C., Testani, E., Campanelli, G., Sestili, S., Leteo, F., Tittarelli, F., … Trinchera, A. (2015).

520   Ecological service providing crops effect on melon-weed competition and allelopathic interactions.

521   *Organic Agriculture*, *5*(3), 199–207. doi: 10.1007/s13165-014-0088-9

522   Cooper, J., Baranski, M., Stewart, G., Nobel-de Lange, M., Bàrberi, P., Fließbach, A., ... & Mäder,

523   P. (2016). Shallow non-inversion tillage in organic farming maintains crop yields and increases

524   soil   C   stocks: a   meta-analysis.   Agron.   Sustain.   Dev.   36,   22   (2016).

525   https://doi.org/10.1007/s13593-016-0354-1

526   Darnhofer, I., Lindenthal, T., Bartel-Kratochvil, R., & Zollitsch, W. (2010). Conventionalisation

527   of organic farming practices: from structural criteria towards an assessment based on organic

528   principles.   A   review.   *Agronomy   for   Sustainable   Development*,   *30*(1),   67–81.   doi:

529   10.1051/agro/2009011

530   De Cicco, A. (2016). The fruit and vegetable sector in the EU - a statistical overview. Retrieved

531   September   18,   2019,   from   Eurostat   statistics   explained   website:

532   https://ec.europa.eu/eurostat/statistics-

533   explained/index.php/The_fruit_and_vegetable_sector_in_the_EU_-_a_statistical_overview

534   Delate, K., Cwach, D., & Chase, C. (2012). Organic no-tillage system effects on soybean, corn

535   and irrigated tomato production and economic performance in Iowa, USA. *Renewable Agriculture*

536   *and Food Systems*, *27*(01), 49–59. doi: 10.1017/S1742170511000524

537   Depalo, L., Burgio, G., Magagnoli, S., Sommaggio, D., Montemurro, F., Canali, S., & Masetti, A.

538   (2020). Influence of Cover Crop Termination on Ground Dwelling Arthropods in Organic

539   Vegetable Systems. *Insects*, *11*(7), 445. doi: 10.3390/insects11070445

540   Diacono, M., Persiani, A., Canali, S., & Montemurro, F. (2018). Agronomic performance and

541   sustainability indicators in organic tomato combining different agro-ecological practices. *Nutrient*

542   *Cycling in Agroecosystems*, *112*(1), 101–117. doi: 10.1007/s10705-018-9933-7

543   Diacono, M., Persiani, A., Fiore, A., Montemurro, F., & Canali, S. (2017). Agro-Ecology for

544   Potential Adaptation of Horticultural Systems to Climate Change: Agronomic and Energetic

545   Performance Evaluation. *Agronomy*, *7*(2), 35. doi: 10.3390/agronomy7020035

546   Ekenler, M., & Tabatabai, M. A. (2003). Effects of liming and tillage systems on microbial

547   biomass and glycosidases in soils. *Biology and Fertility of Soils*, *39*(1), 51–61. doi:

548   10.1007/s00374-003-0664-8

549   Elsoragaby, S., Yahya, A., Mahadi, M. R., Nawi, N. M., & Mairghany, M. (2019). Energy

550   utilization   in   major   crop   cultivation.   *Energy*,   *173*,   1285–1303.   doi:

551   10.1016/J.ENERGY.2019.01.142

552   EUROSTAT. (2019). Crop production in EU standard humidity. Retrieved October 1, 2019, from

553   Last   update: 23-09-2019   website:

554   https://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do

555   Fornasier, F., & Margon, A. (2007). Bovine serum albumin and Triton X-100 greatly increase

556   phosphomonoesterases and arylsulphatase extraction yield from soil. Soil Biology and

557   Biochemistry, 39(10), 2682–2684. doi: 10.1016/j.soilbio.2007.04.024

558   González-Rodríguez, R. M., Rial-Otero, R., Cancho-Grande, B., & Simal-Gándara, J. (2008).

559   Determination of 23 pesticide residues in leafy vegetables using gas chromatography–ion trap

560   mass spectrometry and analyte protectants. *Journal of Chromatography A*, *1196–1197*, 100–109.

561   doi: 10.1016/J.CHROMA.2008.02.087

562   Hefner, M., Canali, S., Willekens, K., Lootens, P., Deltour, P., Beeckman, A., … Kristensen, H.
563   L. (2020). Termination method and time of agro-ecological service crops influence soil mineral
564   nitrogen, cabbage yield and root growth across five locations in Northern and Western Europe.
565   *European Journal of Agronomy*, *120*, 126144. doi: 10.1016/j.eja.2020.126144

566   Hefner, M., Gebremikael, M. T., Canali, S., Sans Serra, F. X., Petersen, K. K., Sorensen, J. N., …

567   Kristensen, H. L. (2020). Cover crop composition mediates the constraints and benefits of roller-

568   crimping and incorporation in organic white cabbage production. *Agriculture, Ecosystems and*

569   *Environment*, *296*, 106908. doi: 10.1016/j.agee.2020.106908

570   Hutchings, N. J., & Kristensen, I. S. (1995). Modelling mineral nitrogen accumulation in grazed

571   pasture: will more nitrogen leach from fertilized grass than unfertilized grass/clover? *Grass and*

572   *Forage Science*, *50*(3), 300–313. doi: 10.1111/j.1365-2494.1995.tb02325.x

573   Jiménez-Valverde, A., Baselga, A., Melic, A., & Txasko, N. (2010). Climate and regional beta-

574   diversity gradients in spiders: dispersal capacity has nothing to say? *Insect Conservation and*

575   *Diversity*, *3*(1), 51–60. doi: 10.1111/j.1752-4598.2009.00067.x

576   Knight, T. R., & Dick, R. P. (2004). Differentiating microbial and stabilized β-glucosidase activity

577   relative to soil quality. *Soil Biology and Biochemistry*, *36*(12), 2089–2096. doi:

578   10.1016/J.SOILBIO.2004.06.007

579   Kornecki, T. S., Price, A. J., Raper, R. L., & Arriaga, F. J. (2009). New roller crimper concepts

580   for mechanical termination of cover crops in conservation agriculture. *Renewable Agriculture and*

581   *Food Systems*, *24*(03), 165–173. doi: 10.1017/S1742170509002580

582   Magagnoli, S., Masetti, A., Depalo, L., Sommaggio, D., Campanelli, G., Leteo, F., … Burgio, G.

583   (2018). Cover crop termination techniques affect ground predation within an organic vegetable

584   rotation system: A test with artificial caterpillars. *Biological Control*, *117*, 109–114. doi:

585   10.1016/J.BIOCONTROL.2017.10.013

586   McGeoch, M. A. (1998). The selection, testing and application of terrestrial insects as

587   bioindicators. *Biological Reviews of the Cambridge Philosophical Society*, *73*(2),

588   S000632319700515X. doi: 10.1017/S000632319700515X

589   Metzger, M. J., Bunce, R. G., Jongman, R. H., Mücher, C. A., & Watkins, J. W. (2005). A climatic

590   stratification of the environment of Europe. *Global Ecology and Biogeography*, *14(6)*, 549–563.

591   doi: 10.1111/j.1466-822x.2005.00190.x

592   Min, J., Zhang, H., & Shi, W. (2012). Optimizing nitrogen input to reduce nitrate leaching loss in

593   greenhouse vegetable production. *Agricultural Water Management*, *111*, 53–59. doi:

594   10.1016/J.AGWAT.2012.05.003

595   Mohammadi, A., & Omid, M. (2010). Economical analysis and relation between energy inputs

596   and yield of greenhouse cucumber production in Iran. *Applied Energy*, *87*(1), 191–196. doi:

597   10.1016/J.APENERGY.2009.07.021

598   Navarro-Miró, D., Blanco-Moreno, J. M., Ciaccia, C., Chamorro, L., Testani, E., Kristensen, H.

599   L., … Sans, F. X. (2019). Agroecological service crops managed with roller crimper reduce weed

600   density and weed species richness in organic vegetable systems across Europe. *Agronomy for*

601   *Sustainable Development*, *39*(6), 55. doi: 10.1007/s13593-019-0597-8

602   Navarro-Miró, D., Iocola, I., Persiani, A., Blanco-Moreno, J. M., Kristensen, H. L., Hefner, M., …

603   Canali, S. (2019). Energy flows in European organic vegetable systems: Effects of the introduction

604   and management of agroecological service crops. *Energy*, *188*, 116096. doi:

605   10.1016/J.ENERGY.2019.116096

606   Niemelä, J. (2000). Biodiversity monitoring for decision-making. *Annales Zoologici Fennici*, Vol.

607   37, pp. 307–317. doi: 10.2307/23735723

608   Peigné, J., Casagrande, M., Payet, V., David, C., Sans, F. X., Blanco-Moreno, J. M., … Mäder, P.

609   (2016). How organic farmers practice conservation agriculture in Europe. *Renewable Agriculture*

610   *and Food Systems*, *31*(01), 72–85. doi: 10.1017/S1742170514000477

611   Pinheiro, J., & Bates, D. (2000). *Mixed-effects models in S and S-PLUS* (Springer-Verlag, Ed.).

612   New York: Springer-Verlag.

613   Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., & R Core Team. (2017). *nlme: Linear and*

614   *Nonlinear Mixed Effects Models*. Retrieved from https://cran.r-project.org/package=nlme

615   Pittelkow, C. M., Linquist, B. A., Lundy, M. E., Liang, X., van Groenigen, K. J., Lee, J., … Kessel,

616   C. (2015). When does no-till yield more? A global meta-analysis. *Field Crops Research*, *183*,

617   156–168. doi: 10.1016/J.FCR.2015.07.020

618   Ponisio, L. C., M'Gonigle, L. K., Mace, K. C., Palomino, J., de Valpine, P., & Kremen, C. (2015).

619   Diversification practices reduce organic to conventional yield gap. *Proceedings of the Royal*

620   *Society B: Biological Sciences*, *282(1799)*. doi: 10.1098/rspb.2014.1396

621   Power, A. G. (2010). Ecosystem services and agriculture: tradeoffs and synergies. *Philosophical*

622   *Transactions of the Royal Society B: Biological Sciences*, *365(1554)*, 2959–2971. doi:

623   10.1098/rstb.2010.0143

624   Pretorius, R. J., Hein, G. L., Blankenship, E. E., Purrington, F. F., Wilson, R. G., & Bradshaw, J.

625   D. (2018). Comparing the Effects of Two Tillage Operations on Beneficial Epigeal Arthropod

626   Communities and Their Associated Ecosystem Services in Sugar Beets. *Journal of Economic*

627   *Entomology*, *111*(6), 2617–2631. doi: 10.1093/jee/toy285

628   R Core Team. (2018). *R: A language and environment for statistical computing*. Retrieved from

629   https://www.r-project.org/

630   Rivers, A., Mullen, C., Wallace, J., & Barbercheck, M. (2017). Cover crop-based reduced tillage

631   system influences Carabidae (Coleoptera) activity, diversity and trophic group during transition

632   to organic production. *Renewable Agriculture and Food Systems*, *32*(6), 538–551. doi:

633   10.1017/S1742170516000466

634   Roger-Estrade, J., Anger, C., Bertrand, M., & Richard, G. (2010). Tillage and soil ecology:

635   Partners for sustainable agriculture. *Soil and Tillage Research*, *111*(1), 33–40. doi:

636   10.1016/J.STILL.2010.08.010

637   Seufert, V., Ramankutty, N., & Mayerhofer, T. (2017). What is this thing called organic? – How

638   organic farming is codified in regulations. *Food Policy*, *68*, 10–20. doi:

639   10.1016/J.FOODPOL.2016.12.009

640   Shirtliffe, S. J., & Johnson, E. N. (2012). Progress towards no-till organic weed control in western

641   Canada. *Renewable Agriculture and Food Systems*, *27*(01), 60–67. doi:

642   10.1017/S1742170511000500

643   Silva, E., Moore, V., Silva, E. M., & Moore, V. M. (2017). Cover Crops as an Agroecological

644   Practice on Organic Vegetable Farms in Wisconsin, USA. *Sustainability*, *9*(1), 55. doi:

645   10.3390/su9010055

646   Sommaggio, D., Peretti, E., & Burgio, G. (2018). The effect of cover plants management on soil

647   invertebrate fauna in vineyard in Northern Italy. *BioControl*, *63*(6), 795–806. doi:

648   10.1007/s10526-018-09907-z

649   Sunderland, K., & Samu, F. (2000). Effects of agricultural diversification on the abundance,

650   distribution, and pest control potential of spiders: a review. *Entomologia Experimentalis et*

651   *Applicata*, *95*(1), 1–13. doi: 10.1046/j.1570-7458.2000.00635.x

652   Tamburini, G., De Simone, S., Sigura, M., Boscutti, F., & Marini, L. (2016). Conservation tillage

653   mitigates the negative effect of landscape simplification on biological control. *Journal of Applied*

654   *Ecology*, *53*(1), 233–241. doi: 10.1111/1365-2664.12544

655   Torrellas, M., Antón, A., Ruijs, M., Victoria, N. G., Stanghellini, C., & Montero, J. I. (2012).

656   Environmental and economic assessment of protected crops in four European scenarios. *Journal*

657   *of Cleaner Production*, *28*, 45–55. doi: 10.1016/J.JCLEPRO.2011.11.012

658   Trewavas, A. (2001). Urban myths of organic farming. *Nature*, *410*(6827), 409–410. doi:

659   10.1038/35068639

660   Trewavas, A. (2004). A critical assessment of organic farming-and-food assertions with particular

661   respect to the UK and the potential environmental benefits of no-till agriculture. *Crop Protection*,

662   *23*, 757–781. doi: 10.1016/j.cropro.2004.01.009

663   Tuomisto, H. L., Hodge, I. D., Riordan, P., & Macdonald, D. W. (2012). Does organic farming

664   reduce environmental impacts? – A meta-analysis of European research. *Journal of*

665   *Environmental Management*, *112*, 309–320. doi: 10.1016/J.JENVMAN.2012.08.018

666   Turner, R. J., Davies, G., Moore, H., Grundy, A. C., & Mead, A. (2007). Organic weed

667   management: A review of the current UK farmer perspective. *Crop Protection*, *26*(3), 377–382.

668   doi: 10.1016/J.CROPRO.2006.01.021

669   Vincent-Caboud, L., Peigné, J., Casagrande, M., & Silva, E. (2017). Overview of Organic Cover

670   Crop-Based No-Tillage Technique in Europe: Farmers' Practices and Research Challenges.

671   *Agriculture*, *7*(5), 42. doi: 10.3390/agriculture7050042

672   Wezel, A., Casagrande, M., Celette, F., Vian, J.-F., Ferrer, A., & Peigné, J. (2014). Agroecological

673   practices for sustainable agriculture. A review. *Agronomy for Sustainable Development*, *34*(1), 1–

674   20. doi: 10.1007/s13593-013-0180-7

675   Zaykin, D. V. (2011). Optimally weighted Z-test is a powerful method for combining probabilities

676   in meta-analysis. *Journal of Evolutionary Biology*, *24*(8), 1836–1841. doi: 10.1111/j.1420-

677   9101.2011.02297.x

678   Zhang, W., Ricketts, T. H., Kremen, C., Carney, K., & Swinton, S. M. (2007). Ecosystem services

679   and dis-services to agriculture. *Ecological Economics*, *64*(2), 253–260. doi:

680   10.1016/J.ECOLECON.2007.02.024

681
682

Table 1. Environmental conditions, cash crops, ASC and factors analysed in each trial. European Climatic Zones according to Metzger et al. (2005).

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
ES	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
	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
IT	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
	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

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; ST-P: Strip-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.' $P > 0.05$; '*' $P \leq 0.05$; '**' $P \leq 0.01$; '***' $P \leq 0.001$.
12

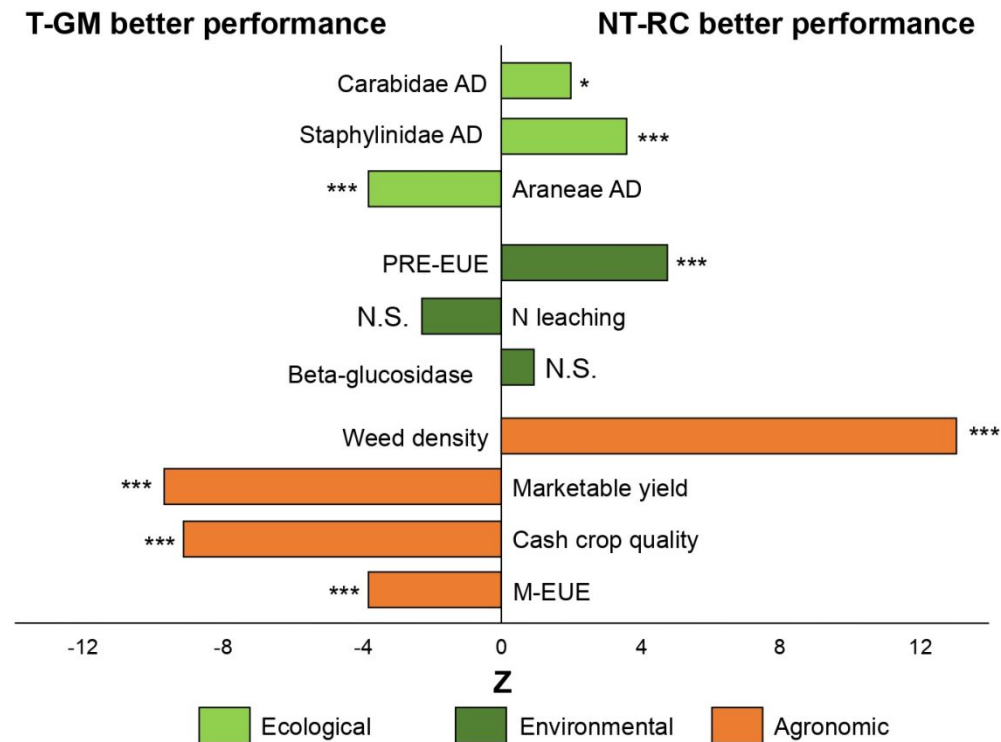|		Ecological indicators			Environmental indicators		
Country	Trial	Carabidae AD	Staphylinidae AD	Araneae AD	PRE-EUE	N leaching	Beta-glucosidase
BE-CRA-W	FtA					1.93 ± 0.91 *	
BE-ILVO	FtA	11.2 ± 2.63 **	-1.29 ± 0.43 *		† 0.37 ± 0.06 ***		
BE-INAGRO	FtA					1.39 ± 1.27 N.S.	0.06 ± 0.05 N.S.
DK	FtA	†††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

13
14 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
15 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
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; ††: 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 ± 0.19 N.S.	-44.52 ± 3.48 ***	
BE-ILVO	FtA				0.04 ± 0.2 N.S.
BE-INAGRO	FtA		-4.12 ± 0.15 ***		
DK	FtA	-474.94 ± 39.13 ***	† -0.2 ± 0.04 **		†† -0.17 ± 0.03 **
EE	FtA	-140.08 ± 41.38 **	†† -0.27 ± 0.08 **	†† -1.77 ± 1.14 N.S.	†† -0.19 ± 0.06 **
ES	FtA	†† -10.98 ± 5.27 *	0.26 ± 0.15 N.S	0.55 ± 0.43 N.S.	0.14 ± 0.05 *
ES	FtB	† -0.77 ± 0.1 ***	-1.3 ± 0.4 **	1.37 ± 1.17 N.S.	-0.34 ± 0.1 **
FR	FtA	† -1.68 ± 0.26 ***	-1.91 ± 0.24 ***	-0.93 ± 0.15 ***	-0.44 ± 0.11 **
IT	FtA	† 0.12 ± 0.16 N.S.	† 0.32 ± 0.15 N.S.	-0.26 ± 0.08 **	† 0.37 ± 0.15 *
IT	FtB	25.44 ± 12.79 N.S.	-0.23 ± 0.12 N.S.	-0.01 ± 0.4 N.S.	-0.11 ± 0.07 N.S.
SI	FtA	†† -8.99 ± 0.34 ***			

22
23 Country abbreviations as in Table 1. Agronomic indicators: M-EUE: energy-use efficiency using the marketable yield as the
24 output of the cropping system. The estimate represents the average difference in the response variable (or its transformation)
25 between NT-RC and T-GM. Positive values imply higher value of the response in NT-RC than in T-GM**.**
26
27

1 **Figure 1.** Graphical representation of the statistical support for the differences in environmental and agronomic performance between T-GM and NT-RC. The
2 bars represent the Z value obtained from the weighted Stouffer's test across trials for each indicator. Significance codes: 'N.S.' $P > 0.05$; '*' $P \leq 0.05$; '**' $P \leq 0.01$;
3 '***' $P \leq 0.001$.

4
5
6
7
8 ASC management strategies: no-till roller crimping (NT-RC) and green manuring (T-GM). Ecological indicators: Carabidae AD: activity density of ground beetles;
9 Staphylinidae AD: activity density of rove beetles; Araneae AD: activity density of spiders; Environmental indicators: PRE-EUE: energy-use efficiency using the potentially
10 recyclable energy as the output of the cropping system; N leaching: nitrogen leaching potential; Beta-glucosidase enzyme. Agronomic indicators: M-EUE: energy-use
11 efficiency using the marketable yield as the output of the cropping system.

Appendix S1. Trial details

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

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

Field experiment type A

Experimental design

The field trial was newly established at the Walloon Agricultural Research Center located in Gembloux, Belgium (BE-CRA-W) (50° 36' 35.45" N and 4° 57' 14.91" E). This location represented the Atlantic Central European climatic zone. During experimentation, the mean annual temperature and rainfall were 10.99 °C and 538 mm, respectively. The trial soil had a silt 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).
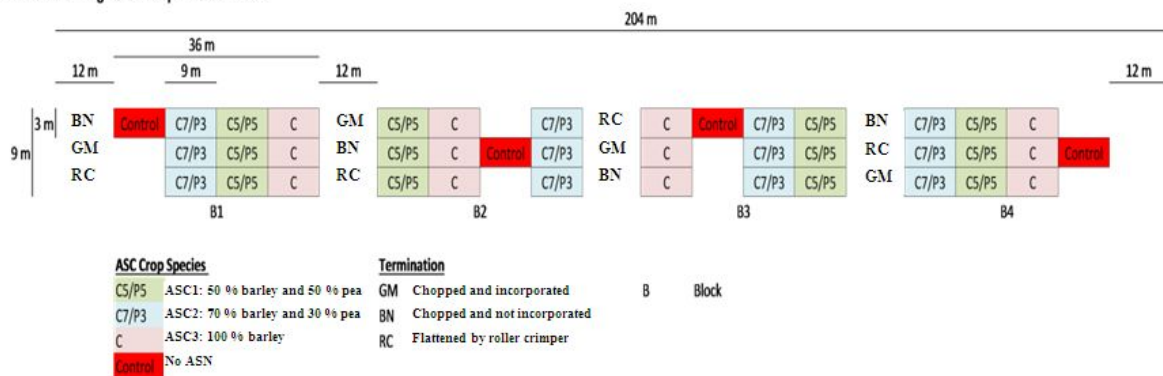
Figure 1. Experimental design of Walloon Agricultural Research Center (BE-CRA-W) trial. ASC composition: C5/P5 (green)- 50 % barley (*Hordeum vulgare* L.) + 50 % pea (*Pisum sativum* L.); C7/P3 (blue)- 70 % barley (*H. vulgare*) + 30 % pea (*P. sativum*); C (pink) – 100 % barley (*H. vulgare*); and Control (red) - No ASC. Termination: GM - Chopped and incorporated (T-GM); BN - Chopped and not incorporated; RC - Flattened by roller crimper (NT-RC).

The three ASC compositions were ASC1: 50 % barley (*Hordeum vulgare* L.) + 50 % pea (*Pisum sativum*), ASC2: 70 % barley (*H. vulgare*) + 30 % pea (*P. sativum*), and ASC3: 100 % 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 (BN), and (3) flattened by roller-crimping (NT-RC). In parallel, a control treatment without plant cover (bare soil, BS) was established. The roller crimper was 3 m wide and weighed 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 × 9 m. The cash crop was red cabbage (*Brassica oleracea* var. *capitata* L. f. rubra).

A)   B)

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**

43   On the 25th August 2016, before ASC sowing, 20 t ha^{-1} of cow manure (82 kg total N ha^{-1}) was

44   applied as fertiliser. The ASCs were sown on the 15th September 2016. In BS plots, four weed

45   control operations, using a rotary harrow, were carried out during the ASC growth period. To

46   simulate farmer practise, ASC termination was carried out on different dates, depending on the

47   ASC management strategy: T-GM on May 5th, CNI on May 23rd, and NT-RC on May 31st,

48   2017.

49   Red cabbage was transplanted on the 31st May 2017, with a row spacing of 0.60 m and a plant

50   spacing of 0.40 m (Picture 2). This cash crop was fertilised during planting, using commercial

51   organic fertiliser containing 60 kg ha^{-1} of nitrogen and 33 kg ha^{-1} of phosphorous. Manual weed

52   control was performed during growth of the cash crop on the 14th July 2017 only in T-GM and

53   BS plots. The mulch in CNI and NT-RC plots provided acceptable weed control. The cash crop

54   did not require irrigation and was harvested manually on the 25th and 26th of October 2017.

55

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-ILVO)

Field experiment type A

Experimental design

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

The experiment was repeated on the same plots during both years. The trial had a split-split-plot randomised complete block design with two factors and four replications. The main plot was the ASC management strategy, and the application of compost was the subplot factor (Figure 2).
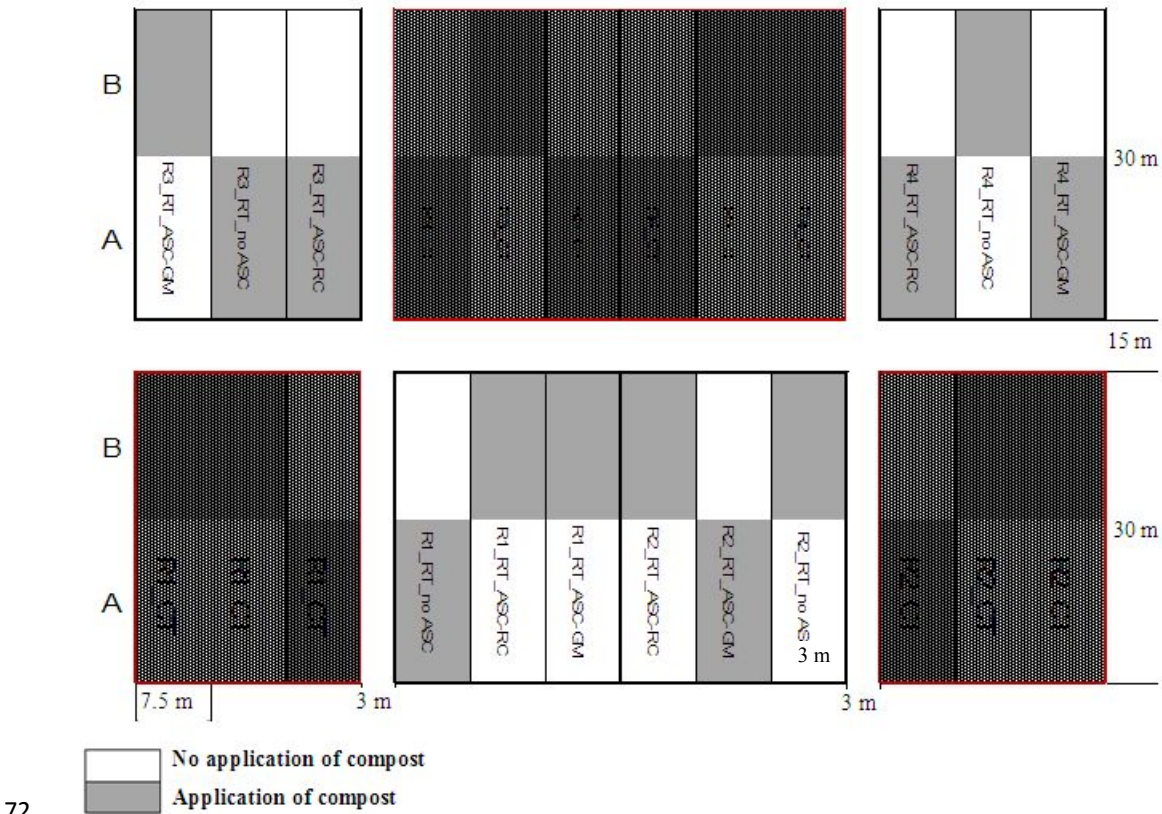
Figure 2 Experimental design of the Research Institute for Agriculture, Fisheries and Food (BE-ILVO) trial.

Termination: R_RT_ASC-GM = ASC chopped and incorporated into the soil (T-GM); R_RT_ASC-RC = ASC

75   flattened by a roller crimper (NT-RC); and R_RT_noASC = Control treatment without ASC. Compost factor: White -

76   No application of compost; Grey - Application of compost.

77   The ASC termination strategies were: (1) roller-crimped (NT-RC), (2) chopped with a flail

78   mower and incorporated into the soil by non-inversion tillage (T-GM). The roller crimper was

79   3.1 m wide, weighed 1,720 kg when filled with oil, and was designed and constructed by ILVO

80   (Picture 3). In the NT-RC plots, furrows for cash crop transplanting were created with a harrow

81   tooth. The ASC was a mixture of 40 % rye (*Secale cereale* L.) and 60 % pea (*Pisum sativum*).

82   Plot size was 7.5 × 15 m. The cash crop was white cabbage (*Brassica oleracea* var. *capitata* L.).

83

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**

88   The ASC was sown on the 5th October 2015, and the 24th November 2016. In T-GM plots, the

89   ASC was terminated by flail mowing on the 20th April 2016 and the 7th May 2017, and by

90   superficial tillage on the 4th May 2016 and the 8th May 2017. The NT-RC plots were terminated

91   on the 26th May 2016 and the 16th June 2017. The cash crop was transplanted and fertilised

92   using a planting machine on the 27th May 2016, and the 21st June 2017 (Picture 4). Mechanical

93   weeding was carried out on the 6th June, 6th, 26th, and 27th July 2016, and on the 13th, 17th, and

94   27th July 2017. Manual weeding was carried out during the periods: 6th to 22nd July, 28th July to

95   4th August, and 5th to 14th September 2016, and on the 14th, 27th, and 28th July 2017. Cash crop

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 3rd and 4th November 2016, and the

98 7th November 2017.

99

100 **Picture 4.** Transplanted white cabbage in an NT-RC plot in the Research Institute for Agriculture, Fisheries, and

101 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).

Belgium - INAGRO (BE-INAGRO)

Field experiment type A

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,

111 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

113 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,

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

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

117

118
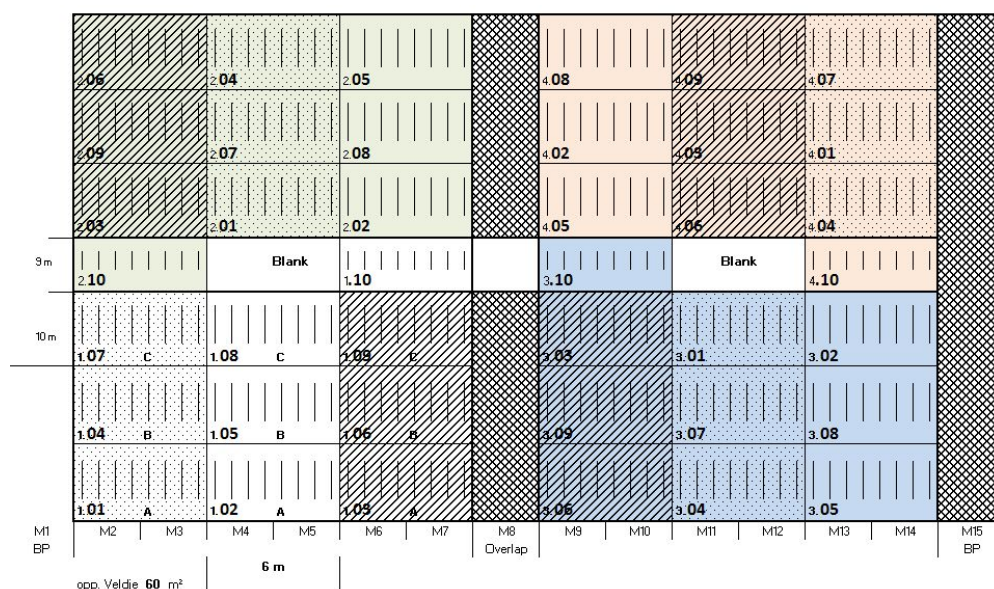
119   **Figure 3.** Experimental design at the INAGRO (BE-INAGRO) organic farm station during the first year.

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

122   (*Pisum sativum*); C - rye-pea mixture; and Blank - No ASC.

123
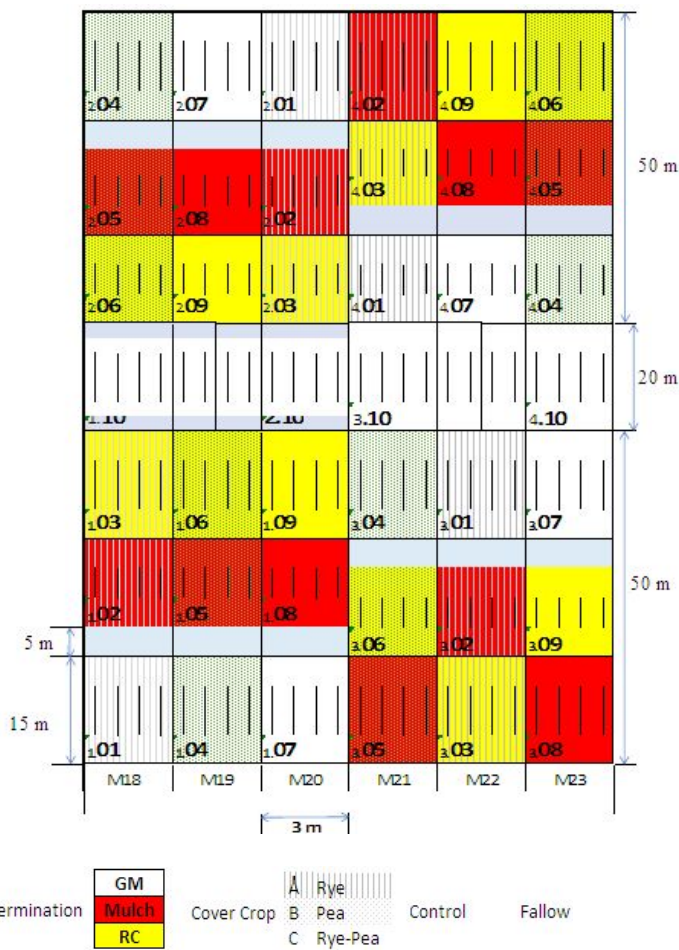
Figure 4. Experimental design at the INAGRO (BE-INAGRO) organic farm station during the second year. Termination: GM (white) - Incorporation by mill cutting one month before planting (T-GM); Mulch (red) - Mulching by flail mowing at planting (not-incorporated); and RC (yellow) - Roller crimper (NT-RC). ASC composition: A (vertical lines) - Winter rye (*Secale cereale*); B (small dots) - Winter pea (*Pisum sativum*); and C (no pattern) Rye-pea mixture.

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 year, the ASC management strategies analysed were: (1) roller crimper early termination, (2) roller crimper late termination, and (3) mill cutting and non-inversion tillage, one month before planting (T-GM). The roller crimper early termination treatment was scheduled to coincide with the time of pea flowering (i.e., one week before cash crop transplanting) and the roller crimper late termination treatment, at the time of rye flowering (i.e., one day before planting of the cash crop). In the second year, the ASC management strategies studied were: (1) incorporation by mill cutting (MC) one month before planting (T-GM), (2) mulching by flail mowing at planting

140 (not-incorporated), and (3) roller crimping (NT-RC). In this trial, the roller crimper used for

141 ASC management was the same as in the ILVO trial (Picture 5.A) and furrows for cash crop

142 transplanting were created by in-line tillage (Picture 5.B). Additionally, during both years, a

143 control treatment that did not use ASC and standard soil management was set-up. Plot size was

144 6×10 m (except the fallow plots: 6×9 m) during the first year and 3×15 m during the second

145 year. The cash crop was white cabbage (*Brassica oleracea* var. *capitata*).

146

147 **Picture 5.** Machinery used for NT-RC management at the INAGRO (BE-INAGRO) organic farm station. A - Roller

148 crimper; B - In-line tiller.

Agronomic management

150 The trial was fertilised with composted farm yard manure (10 ton ha^{-1}) on October 12th, 2015,

151 and with commercial organic fertiliser (Organic plant feed (OPF) granulate 11-0-5, Plant Health

152 Cure B.V., Nederland) on March 16th, 2017. The ASC was sown on October 13th, 2015 and

153 October 28th, 2016. During the first year, the ASC was terminated with the T-GM strategy on

154 April 28th, 2016 and with the NT-RC strategy on May 23rd, 2016. During the second year,

155 termination happened on April 18th, 2017 in the T-GM plots, and on May 24th, 2017 in the NT-

156 RC plots.

157 White cabbage was transplanted, with a row spacing of 0.70 m and a plant spacing of 0.30 m,

158 using a planting machine on May 25th, 2016 and on May 30th, 2017 (Picture 6). The cabbages

159 were fertilised with 50 kg N ha^{-1} commercial organic fertiliser (OPF granulate 11-0-5) on July

160 8th, 2016, during the first cycle, and on May 31st, 2017 during the second cycle. The cash crop

161 was irrigated on August 24th, and 31st, 2016, and only once at the time of cash crop

162 transplantation in 2017. In NT-RC plots, weeding operations were not required during the cash

163 crop cycle. In T-GM plots, in the first year, weeding operations during the cash crop cycle were

164 carried out by hoeing (June 8th, 2016) harrowing (June 9th, 2016) and manually (July 20th, and

165 22nd, 2016). In the second year, T-GM plots were weeded by mechanical weed control (June

166 15th, 2017) and manually (June 15th, and July 6th, 2017). The cash crop harvest was performed

167 on November 21st, 2016 and November 7th, 2017. More information about this trial can be found

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

169

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

171 station.

172 Denmark (DK)

173 **Field experiment type A**

174 **Experimental design**

175 The field trial was newly established at the Department of Food Science research centre of

176 Aarhus University, located in Årslev, Denmark (55º 18′ N and 10º 27′ E), in the Atlantic North

177 European climatic zone. The mean annual temperature was 9.3 °C and the mean annual rainfall,

178 614 mm during the first cycle (2015–2016), and 9.1 °C and 673 mm during the second cycle

179 (2016–2017), respectively. The soil had a sandy loamy texture and a 1 % organic carbon

180 content.

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

182   area for the 2016–2017 cycle. The two locations had been managed according to Danish organic

183   farming regulations since 1996 and 2014, respectively. The previous crop grown in the area was

184   barley (*Hordeum vulgare* L.). The trial had a split-plot randomised complete block experimental

185   design with three replications, where ASC management was the whole-plot factor and ASC

186   composition, the subplot factor. The experimental design was modified each year (Figures 5 and
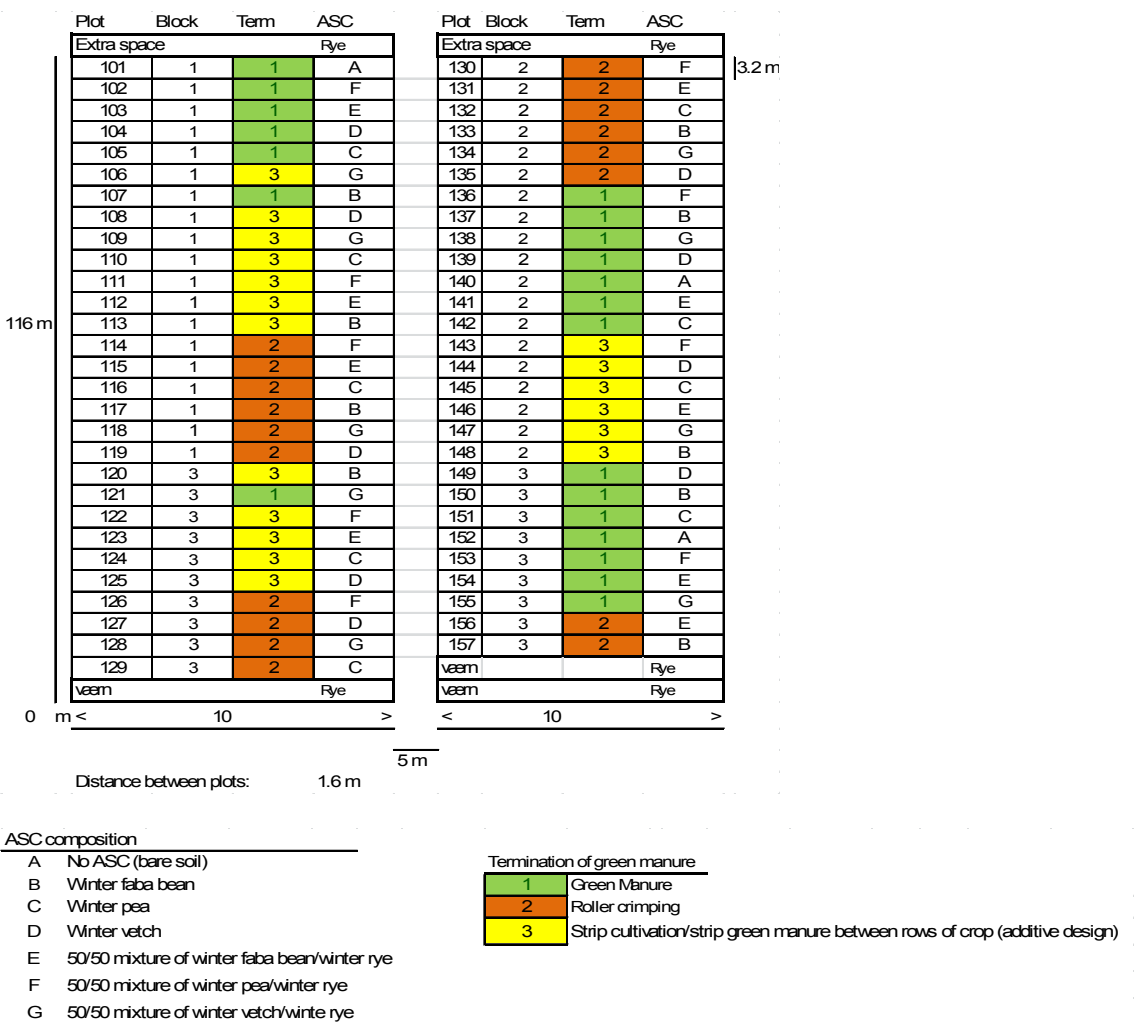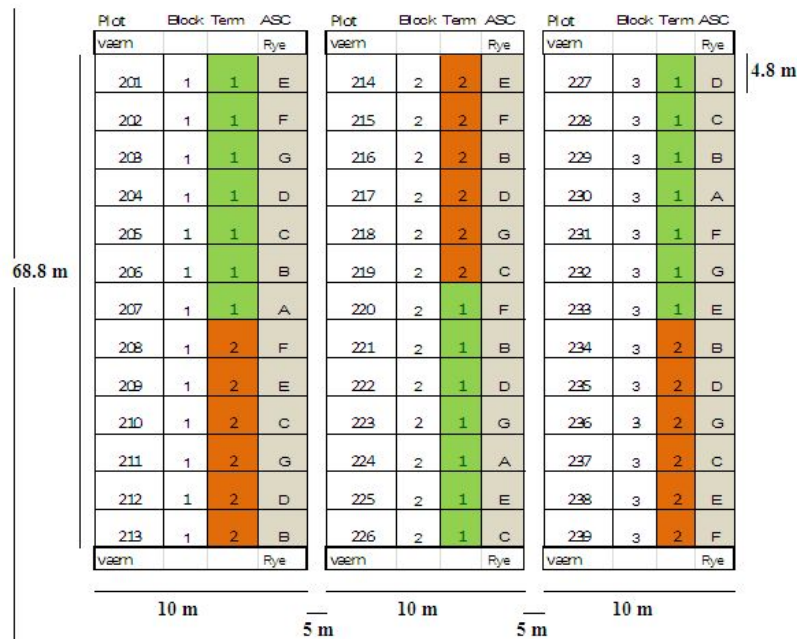
187   6).

Plot	Block	Term	ASC		Plot	Block	Term	ASC
Extra space			Rye		Extra space			Rye
101	1	1	A		130	2	2	F
102	1	1	F		131	2	2	E
103	1	1	E		132	2	2	C
104	1	1	D		133	2	2	B
105	1	1	C		134	2	2	G
106	1	3	G		135	2	2	D
107	1	1	B		136	2	1	F
108	1	3	D		137	2	1	B
109	1	3	G		138	2	1	G
110	1	3	C		139	2	1	D
111	1	3	F		140	2	1	A
112	1	3	E		141	2	1	E
113	1	3	B		142	2	1	C
114	1	2	F		143	2	3	F
115	1	2	E		144	2	3	D
116	1	2	C		145	2	3	C
117	1	2	B		146	2	3	E
118	1	2	G		147	2	3	G
119	1	2	D		148	2	3	B
120	3	3	B		149	3	1	D
121	3	1	G		150	3	1	B
122	3	3	F		151	3	1	C
123	3	3	E		152	3	1	A
124	3	3	C		153	3	1	F
125	3	3	D		154	3	1	E
126	3	2	F		155	3	1	G
127	3	2	D		156	3	2	E
128	3	2	G		157	3	2	B
129	3	2	C		værn			Rye
værn			Rye		værn			Rye

116 m   0 m < —— 10 —— >   < —— 10 —— >   3.2 m   5 m

188   Distance between plots: 1.6 m

ASC composition
A   No ASC (bare soil)
B   Winter faba bean
C   Winter pea
D   Winter vetch
E   50/50 mixture of winter faba bean/winter rye
F   50/50 mixture of winter pea/winter rye
189   G   50/50 mixture of winter vetch/winter rye

Termination of green manure
1   Green Manure
2   Roller crimping
3   Strip cultivation/strip green manure between rows of crop (additive design)

190   **Figure 5.** Experimental design of the organic farm station of the Department of Food Science research center of

191   Aarhus University (DK) during the first cycle (2015–2016). Termination: 1 (green) - Chopped with a flail mower and

192   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 rye and 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 soil with a cultivator as green manure (T-GM), (2) roller-crimped (NT-RC), and (3) strip cultivation/strip green manure between crop rows (additive design). The roller crimper was 2 m wide and weighed 932 kg. It was designed and constructed by Soldo Macchine Agricole (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 bean (*Vicia faba* L.), C: winter pea (*Pisum sativum*), D: winter vetch (*Vicia sativa* L.), E: 50/50 mixture of winter rye (*Secale cereale*) and winter faba bean, F: 50/50 mixture of winter rye and

212   winter pea, and G: 50/50 mixture of winter rye and winter vetch (Picture 8). A control treatment

213   of winter fallow (bare soil) was also included. Plot size was 3.2 × 10 m during the first year and

214   4.8 × 10 m during the second year. The cash crop was white cabbage (*Brassica oleracea* var.

215   *capitata*).

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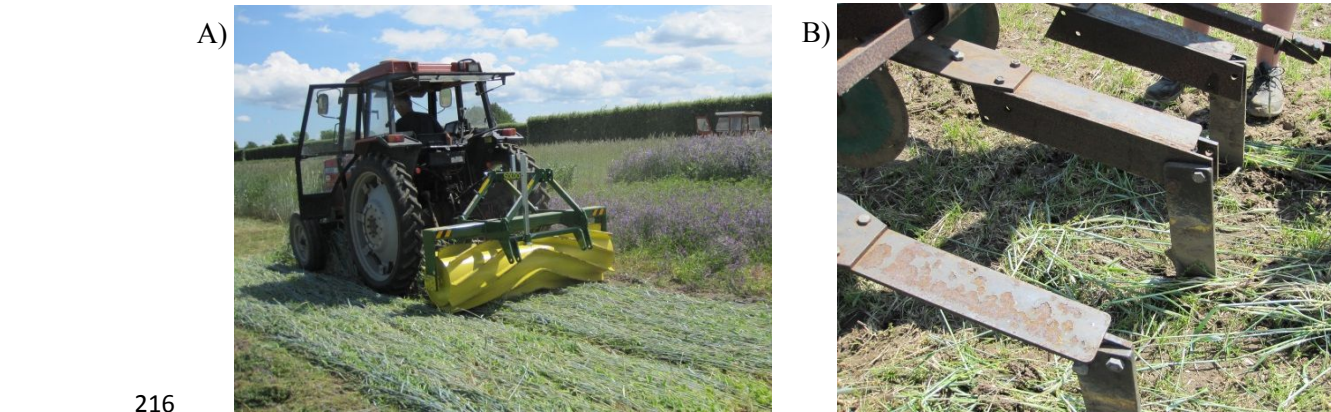
Picture 7. Machinery used for NT-RC management in the DK trial. A - Roller crimper; B - Harrow tooth used to

218   create the cash crop transplanting furrows.

219   **Agronomic management**

220   The trial was fertilised with 200 kg ha^{-1} of feather meal pellets (N-P-K: 13-0-0.4) (26 kg N ha^{-1})

221   on September 9th, 2015 and September 28th, 2016. The ASCs were sown on October 5th, 2015

222   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.

225   White cabbage was transplanted using a three-row planting machine on July 1st, 2016, and on

226   June 21st, 2017, with a row spacing of 0.5 m and a plant spacing of 0.5 m. Weed management

227   was carried out in T-GM plots using a weed-brush machine in inter-rows on July 27th–29th and

228   August 19th, 2016, and July 17th–19th, 2017, and manually with a hoe in inter-rows and intra-

229   rows on September 26th–30th, 2016 and August 10th–22nd, 2017. In NT-RC plots, weeding

230   operations consisted of the manual removal of above ground biomass of large weeds. During the

231   first year, cabbages were fertilised with 50 kg N ha^{-1} feather meal pellets on August 25th, 2016.

232   During the second year, cash crop fertilisation with 100 kg N ha^{-1} feather meal pellets was

233   carried out a week before cabbage transplantation. Thirty kg N ha^{-1} lupine seeds (N-P-K: 4.5-

234   0.4-0.9) were applied on June 15th, 2017, and 80 kg N ha^{-1} feather meal pellets on August 24th,

235   2017. Cash crop irrigation was only required during the first year and was conducted twice (in

236   August and September) with sprinklers. The cabbage crop was harvested on November 11th,

237   2016, and November 2nd, 2017.

238   More information about this trial can be found in Navarro-Miró, Iocola, et al. (2019) Navarro-

239   Miró, Blanco-Moreno, et al. (2019), Hefner, Gebremikael, et al (2020) and Hefner, Canali, et al.

240   (2020).

241   **Estonia (EE)**

242   **Field experiment type A**

243   **Experimental design**

244   The field trial was newly established in an experimental organic research field at Jõgeva in

245   eastern Estonia (EE) (58° 44' N and 26° 24' E), located in the Nemoral European climatic zone.

246   In the first cycle (2015–2016), the mean annual temperature was 6.0 °C and the mean annual

247   rainfall, 825 mm, and in the second cycle (2016–2017) these environmental factors were 5.8 °C

248   and 694 mm, respectively. The trial soil had a clay loamy texture and a 3 % organic carbon

249   content.

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

251   area for the 2016–2017 cycle. The trial was established in an area certified organic from 2005.

252   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

254 factor, and three replicates per treatment (Figure 7).
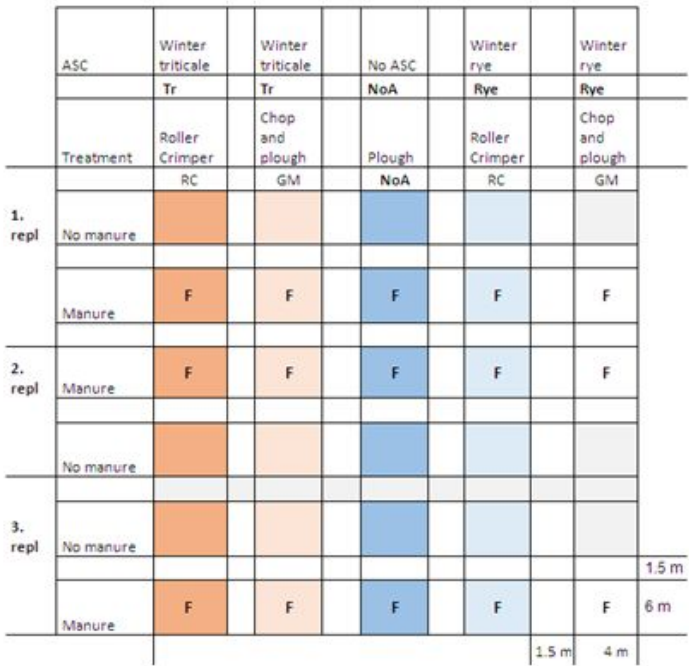
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256 **Figure 7.** Experimental design of the research field at the organic farm station at Jõgeva in eastern Estonia (EE).

257 Termination: RC - Roller-crimped (NT-RC); and GM - Chopped by a flail mower, then ploughed and levelled by a

258 cultivator (T-GM). ASC composition: ASC1 - 100 % Winter rye; and ASC2 - 100 % Winter triticale. NoA - Control

259 treatment without ASC (No ASC). Fertiliser factor: 1) Application of 30 t ha^{-1} solid cattle manure; 2) Not fertilised.

260 The two ASC termination strategies were: (1) roller-crimped (NT-RC), and (2) chopped by a

261 flail mower, then ploughed, and levelled by a cultivator (T-GM). The roller crimper was 2 m

262 wide and weighed 800 kg during the first year ASC termination, and 1,200 kg during the

263 second, and was designed and constructed by Soldo Macchine Agricole (Grassano, Italy)

264 (Picture 9). In the NT-RC plots, furrows for cash crop transplanting were created by in-line

265 tillage (Picture 9). The ASC species composition was: ASC1 - 100 % winter rye (*Secale*

266 *cereale*) (180 kg ha^{-1}), and ASC2 - 100 % winter triticale (× *Triticosecale blaringhemii*

267 A.Camus) (155 kg ha^{-1}). The fertilisation factor consisted of: (1) application of 30 t ha^{-1} solid

268 cattle manure (153 kg ha^{-1} N, 57 kg ha^{-1} P, and 81 kg ha^{-1} K), and (2) no fertiliser. Plot size was

269 6 × 4 m. The cash crop was white cabbage (*Brassica oleracea* var. *capitata*).

270

Picture 9. Machinery used for NT-RC management in the organic research field at Jõgeva in eastern Estonia (EE). A

tractor equipped with a roller crimper and an in-line tiller.

Agronomic management

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

manure compost (12 kg ha^{-1} N, 1.2 kg ha^{-1} P, and 4.8 kg ha^{-1} K). During the first cycle, the

ASCs were sown on August 25th, 2015 and terminated by NT-RC on June, 6th and June 9th,

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.

White cabbage was manually transplanted in the first year from the 13th to 16th June 2016, and

in the second year on June 19th, 2017, with a row spacing of 0.65 m and a 0.50 m plant spacing

(Picture 10). Manual weeding was carried out in all treatments on August 27th, 2016 and July

27th, 2017.

284

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

286   During the first year, the cash crop was not irrigated, whereas during the second year, all plants

287   were watered once in mid-July with a humic solution (0.0003 kg ha^{-1} N, 0.0001 kg ha^{-1} P, and

288   0.0002 kg ha^{-1} K). The cash crop harvest was performed on October 7th, 2016, and from October

289   4th to 6th, 2017.

290   More information about this trial can be found in Tamm, Bender, Nugis, Edesi, & Võsa, (2018),

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

292   Canali, et al. (2020).

293   **Spain (ES)**

294   **Experimental design**

295   Both parallel field experiments type A (FtA) and type B (FtB) were newly established in the

296   Gallecs Area of Natural Interest, Barcelona, Spain (ES) (41° 33' N and 2° 12' E), located in the

297   Mediterranean North European climatic zone. In FtA, during the first cycle (2015–2016), the

298   mean annual temperature was 16.5 °C and the mean annual rainfall, 406 mm, and during the

299   second cycle (2016–2017), 16.1 °C and 409 mm, respectively. In FtB, during the first cycle

300   (2014–2015), the mean annual temperature was 16.1 °C and the mean annual rainfall, 344 mm,

301   and in the second cycle (2015–2016), 16.5 °C and 406 mm, respectively. The trial soil had a

302   loamy texture and contained an average of 0.95 % organic carbon content.

303   In both trials, the field experiments were repeated in the same area in both years. Conversion of

304   the experimental area to organic farming began in 2005, and the previous crop grown in the area

305   was wheat. The experimental design of the FtA and FtB trials was a randomised strip-plot with

306   two factors (ASC composition and ASC management strategy) and four replicates. The different

307   treatments were defined in randomly distributed parallel bands, and within each band, four plots

308   (6 × 4 m) were established. The experimental layout was designed to facilitate traffic of

309   machinery between plots and to enable the agricultural practices to be performed in the same

310   direction.

311   In FtA and FtB, the two ASC termination strategies were: (1) ASCs flattened by a roller crimper

312   (NT-RC), and (2) ASCs mown and chopped and incorporated into the soil as green manure

313   using a chisel plough (T-GM). The roller crimper was 3 m wide and weighed 800 kg when

314   filled with oil, and was designed and constructed by Soldo Macchine Agricole (Grassano, Italy)

315   (Picture 11.A). In the NT-RC plots, furrows for cash crop transplanting were created by in-line

316   tillage (Picture 11.B). Both termination methods were compared to a control treatment without

317   ASC (bare soil).

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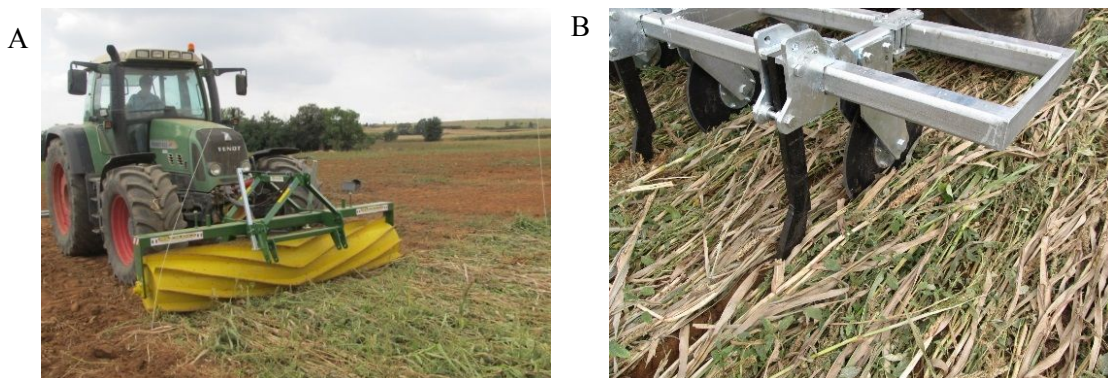
Picture 11. Machinery used for NT-RC management in the Gallecs Area of Natural Interest, Barcelona, Spain

326   (ES). A - Roller crimper. B - In-line tiller.

327

328   **Field experiment type A**

329   In FtA, three ASC compositions and one No ASC treatment were established: ASC1 – 100 %

330   cereal mixture (81 % *Avena byzantina* K.Koch and 19 % *Hordeum vulgare*) (200 kg ha^{-1}),

331   ASC2 - 70 % cereal mixture (140 kg ha^{-1}) + 30 % *Vicia sativa* (75 kg ha^{-1}), ASC3 - 50 % cereal

332   mixture (100 kg ha^{-1}) + 50 % *V. sativa* (125 kg ha^{-1}), and No ASC - spontaneous vegetation

333   without sowing any ASC (Figure 8) . The cash crop was green pepper (*Capsicum annuum* L.)
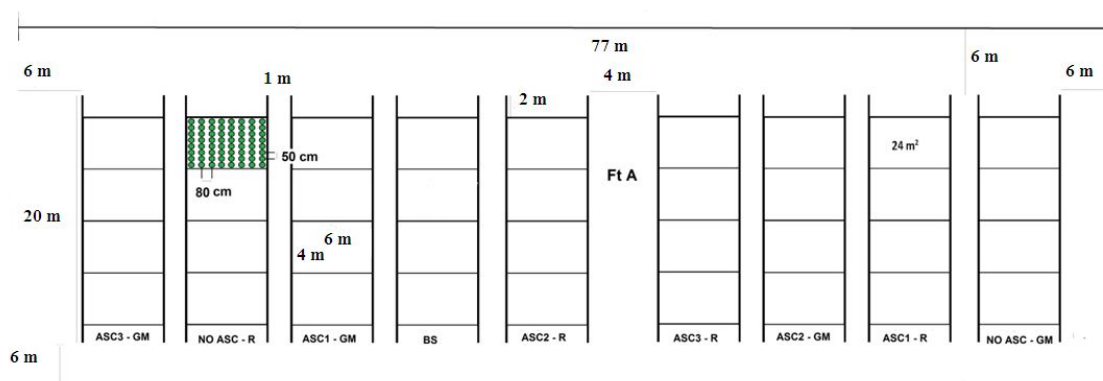
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Figure 8. Experimental design of field experiment type A established in the Gallecs Area of Natural Interest, Barcelona, Spain (ES). Termination: ASC-R - Flattened by roller crimper (NT-RC); and ASC-GM - mowed, chopped and incorporated into the soil 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).

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*).

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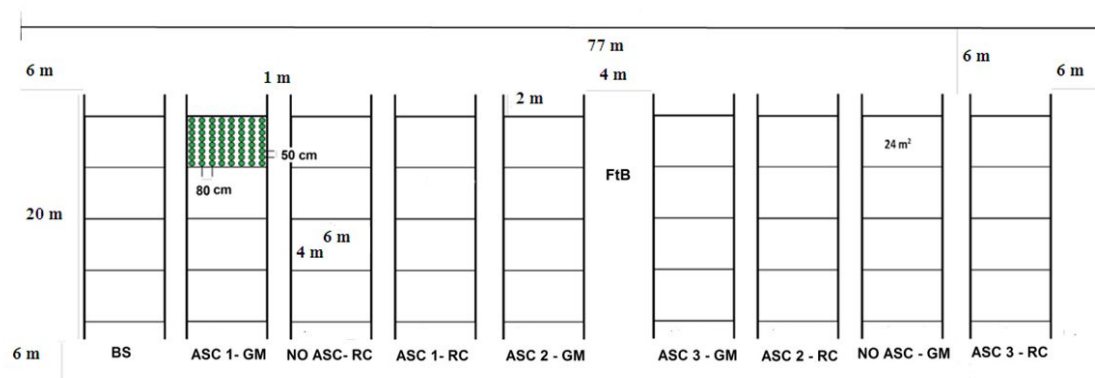
Figure 9. The experimental design of the FtB field experiment established in the Gallecs Area of Natural Interest, Barcelona, Spain (ES). Termination: ASC-R - Flattened by roller crimper (NT-RC); and ASC-GM - mowed, chopped and incorporated into the soil as green manure using a chisel plough (T-GM).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

351   *S. bicolor*; and No ASC - spontaneous vegetation without sowing any ASC. BS - control treatment maintaining the

352   soil without plant cover (bare soil).

Agronomic management

Field experiment type A

355   The ASCs were sown on November 19th, 2015 and January 9th, 2016. In the NT-RC plots, ASC

356   management was carried out on May 4th, 2016 and May 18th, 2017, and creation of the

357   transplanting furrows was carried out along with the NT-RC by in-line tillage on June 24th, 2016

358   and June 13th, 2017.

359   In the T-GM plots, ASC chopping was carried out on May 4th, 2016 and May 18th, 2017, and the

360   incorporation of the plant material into the soil was performed on May 18th, 2016 and June 1st,

361   2017. The green pepper crop were transplanted on May 26th, 2016, and on June 20th, 2017, with

362   a row spacing of 0.80 m and a 0.50 m plant spacing (Picture 12). The cash crop was fertilised

363   just after transplantation with 170 kg ha^{-1} N using commercial organic fertiliser and the green

364   pepper plants were drip-irrigated according to their needs. During the first year, T-GM plots

365   were weeded four times, whereas NT-RC plots only required two weeding operations. During

366   the second year, all plots required three weeding operations. In the first year, the cash crop

367   harvest was performed weekly from July 18th to October 3rd, 2016, whereas in the second year

368   the harvest took place from August 21st to October 2nd, 2017.

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

371   (ES) during growth of the cash crop.

Field experiment type B

The ASCs were sown on April 30th, 2015 and on May 4th, 2016, and irrigated with sprinklers during their development. During the first cycle, the ASCs were managed by two passes of NT-RC on July 23rd and 27th, 2015 and one operation combining NT-RC and in-line tillage on July 29th, 2015. In the T-GM plots, the ASCs were chopped on July 23rd, 2015 and incorporated into the soil using a chisel plough on July, 28th, 2015. During the second cycle, NT-RC management was carried out on August 26th, 2016, and the creation of the transplanting furrows was carried out along with the NT-RC by in-line tillage on September 6th, 2016. In the T-GM management plots, chopping of the ASC was carried out on August 26th, 2016, and incorporation of plant material into the soil was performed on September, 6th, 2016. The savoy cabbages were transplanted on August 4th, 2015, and September 20th, 2016, with a row spacing of 0.80 m and a 0.50 m plant spacing (Picture 13). The cash crop was fertilised with 100 kg ha^{-1} N in both years. During the first year, the commercial organic fertiliser was split into two applications: (1) just after savoy cabbage transplantation and (2) during savoy cabbage development. During the second year, the commercial organic fertiliser was applied just after the savoy cabbage was 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, two weeding operations were required. The savoy cabbages were harvested on December 2nd, 2015, and February 22nd, 2017.

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).

France (FR)

Field experiment type A

Experimental design

399 The field experiment was newly established at the experimental organic research centre of the

400 Groupe de Recherche en Agriculture Biologique (GRAB) in Avignon, southern France (FR)

401 (43° 54' 23.8" N and 4° 53' 06.4" E). This location represented the Mediterranean North

402 European climatic zone. During the first cycle (2015–2016), the mean annual temperature was

403 15.5 °C and the mean annual rainfall, 521 mm, and in the second cycle (2016–2017) these

404 environmental factors were 15.3 °C and 558 mm, respectively. The trial soil had a clay loam

405 texture and a 1.86 % organic carbon content.

406 The experiment was repeated on the same plots in both years, but with some changes in the

407 second year. The selected experimental field had been under organic farming management from

408 2000. The previous crops grown were diversified varieties of squash (*Cucurbita* sp.). The trial

409 had a randomised strip-plot experimental design with three replicates during the first year and

410 four during the second year, where ASC management strategy (i.e., NT-RC or T-GM) was the

411 strip factor, and the ASC composition was the subplot factor (i.e., six different ASC

412 compositions). The experimental design was modified each year (Figures 10 and 11).

Figure 10. First cycle (2015–2016) experimental design of the trial established at the experimental organic research centre of the Groupe de Recherche en Agriculture Biologique (GRAB) in Avignon (FR). Termination: RC - Cover crop flattened by a roller crimper + in-line tillage to create the transplanting furrows (NT-RC); and GM - Termination as a green manure by mowing, chopping, and incorporation of the cover crop into the soil (T-GM). ASC composition: ASC1 - 50 % *Secale cereale* + 50 % *Pisum sativum*; ASC2 - 30 % *S. cereale* + 40 % *Vicia faba* + 40 % *Vicia villosa*; ASC3 - 50 % *Hordeum vulgare* + 37 % *V. faba* + 40 % *P. sativum*; and Control - Control treatment maintaining the soil without plant cover (bare soil).
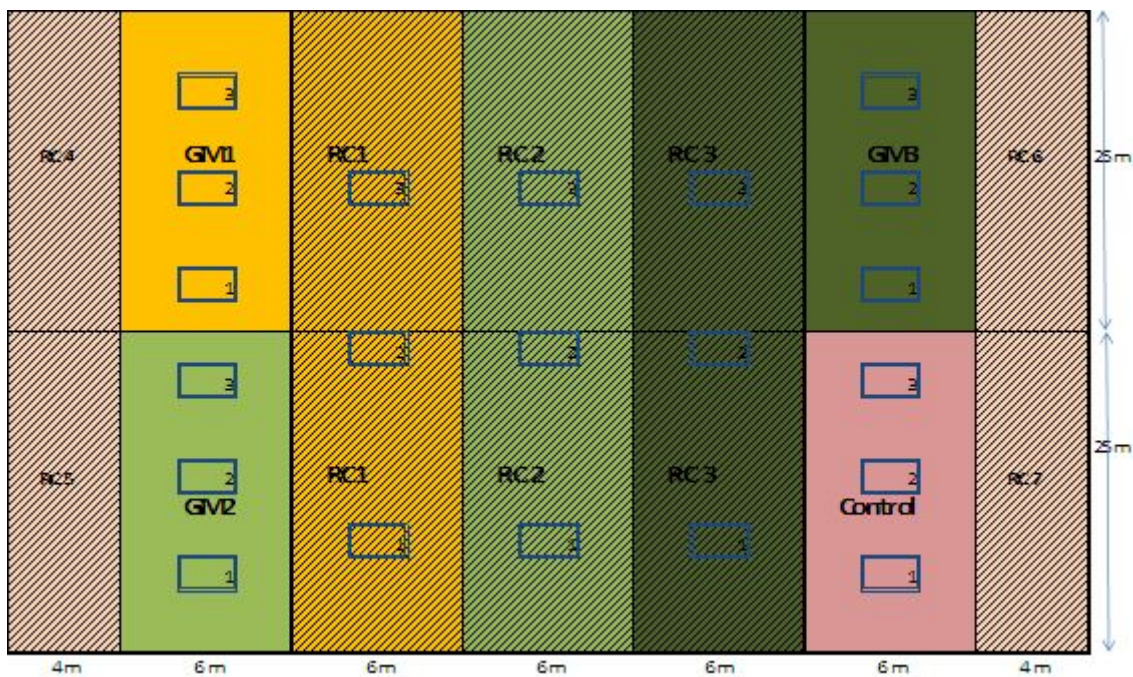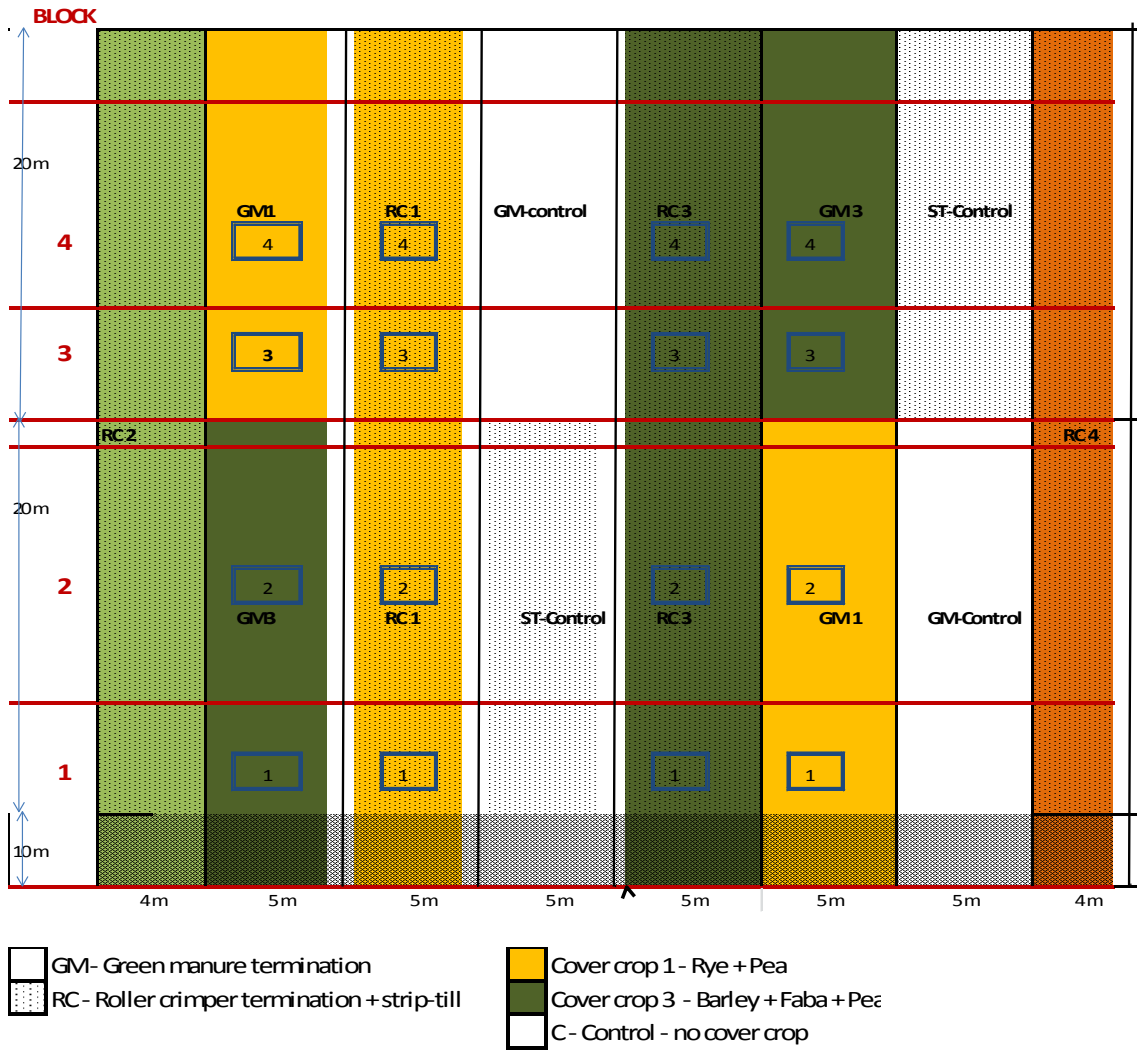
Figure 11. Second cycle (2016–2017) experimental design of the trial established at the experimental organic
research centre of the Groupe de Recherche en Agriculture Biologique (GRAB) in Avignon (FR). Termination: RC -
Cover crop flattened by a roller crimper + in-line tillage to create the transplanting furrows (NT-RC); and GM -
Termination as a green manure by mowing, chopping, and incorporation of the cover crop into the soil (T-GM). ASC
composition: ASC1 – 50 % *Secale cereale* + 50 % *Pisum sativum*; and ASC3 - 50 % *Hordeum vulgare* + 37 % *Vicia
faba* + 40 % *P. sativum*. Additionally, two Control treatments maintaining the soil without plant cover (bare soil)
were established: ST-control - Strip tillage before cash crop transplantation; and GM-control.

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
mowing, chopping, and incorporation of the cover crop into the soil (T-GM). The roller crimper
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
crimper used in the FR trial was self-built in co-operation with *L'atelier Paysan.* During the

437 first year, the ASC species composition was: ASC1: 50 % *Secale cereale* (60 kg ha^{-1}) + 50 %

438 *Pisum sativum* (80 kg ha^{-1}), ASC2: 30 % *S. cereale* (40 kg ha^{-1}) + 40 % *Vicia faba* (80 kg ha^{-1}) +

439 40 % *Vicia villosa* Roth (20 kg ha^{-1}), and ASC3: 50 % *Hordeum vulgare* (50 kg ha^{-1}) + 37 % *V.*

440 *faba* (73 kg ha^{-1}) + 40 % *P. sativum* (67 kg ha^{-1}). In the second year, only two of the previous

441 ASC compositions were sown: ASC1 - 50 % *S. cereale* (60 kg ha^{-1}) + 50 % *P. sativum* (80 kg

442 ha^{-1}), and ASC3 - 50 % *H. vulgare* (50 kg ha^{-1}) + 37 % *V. faba* (73 kg ha^{-1}) + 40 % *P. sativum*

443 (67 kg ha^{-1}). Plot size was 10 × 6 m during the first year and 10 × 5 m during the second year.

444 The cash crop was butternut squash (*Cucurbita moschata* Duchesne cv. 'Ariel').

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 in-

448 line tiller.

449 **Agronomic management**

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

451 and 6 t ha^{-1} 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 19th, 2017 in the RC3 plots and May 16th, 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^{-1}

458   N was applied with the commercial organic fertiliser on June 6th, 2016. In the second year, 72

459   kg ha-1 N was applied with the commercial organic fertiliser on May 31st, 2017 (i.e., before soil

460   tillage and cash crop transplantation) in the T-GM treatments, and localised in the strip-till lines

461   on June 6th, 2017 in the NT-RC treatments. During both years, butternut squash was irrigated by

462   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).

466   In the first year, weeding operations were performed in the inter-rows of the T-GM1 and T-

467   GM2 plots using a rototiller on June 22nd, 2016, and manual weeding was performed three times

468   in all treatments on the 23rd of June, 12th of July and 9th of August, 2016. During the second

469   year, manual weeding was performed twice in all treatments on the 23rd of June, and 5th of July

470   2017. The cash crop was manually harvested on September 7th, 2016, and September 11th, 2017.

471   More information can be found in Navarro-Miró, Iocola, et al. (2019).

472   Italy (IT)

473   Both parallel field experiments Type A (FtA) and Type B (FtB) were newly established at the

474   Experimental Farm of Metaponto belonging to the Consiglio per la Ricerca in Agricoltura e

475   l'Analisi dell'Economia Agraria (CREA) in southern Italy (IT) (40º 24′ N and 16° 48′ E). This

476   location represented the Mediterranean North European climatic zone. In FtA, during the first

477   cycle (2015–2016), the mean annual temperature was 16.7 °C and the mean annual rainfall, 539

478   mm, and during the second cycle (2016–2017) these environmental factors were 16.5 °C and

479   402 mm, respectively. In FtB, during the first cycle (2014–2015) the mean annual temperature

480   was 16.6 °C and the mean annual rainfall, 470 mm, and during the second cycle (2015–2016),

481   these environmental factors were 16.7 °C, and 539 mm, respectively. The trial soil had a clay

482   texture and contained on average 1.1 % organic carbon content.

483   In both trials, the field experiments were not repeated on the same plots in both years and were

484   moved to an adjacent area for the second cycle. Plot size was 6 × 4 m. The two ASC

485   management strategies were: (1) roller-crimped (NT-RC) + in-line tillage to create the

486   transplanting furrows, and (2) chopped and ploughed under and incorporated into the soil by

487   milling (T-GM). The roller crimper was 2.25 m wide and weighed 550 kg and was designed and

488   constructed by Soldo Macchine Agricole (Grassano, Italy) (Picture 16). In the NT-RC plots,

489   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**

496   The previous crop grown in the area was fennel (*Foeniculum vulgare* Mill.). The experimental

497   layout consisted of a split-split-plot with main plots arranged as a randomised complete block

498   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
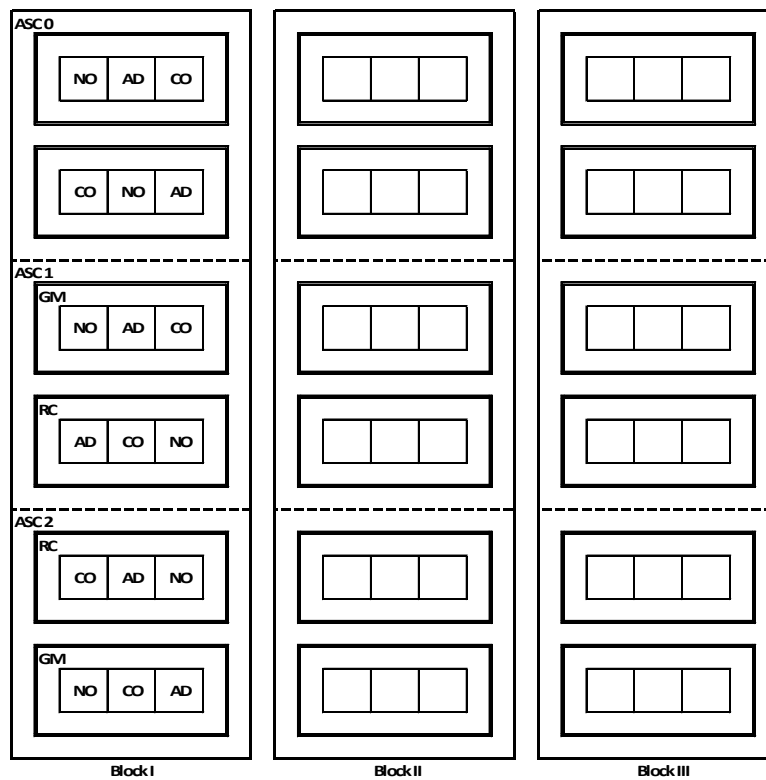
500   factor (Figure 12).

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.

509   The ASC species composition was: ASC1 - *Hordeum vulgare* 20 % + 80 % *Vicia sativa*, and

510   ASC2 – *H. vulgare* 20 % + 80 % *Vicia faba* var. *minor*. The fertilisation factor consisted of: (1)

511   no fertiliser (NO), (2) commercial organic mineral fertiliser allowed in organic farming (CO),

512   and (3) anaerobic digestate from cattle residues (AD). The cash crop was tomato

513   (*Solanum lycopersicum* L.).

514   **Field experiment type B**

515   The previous crop was wheat (*Triticum aestivum* L.). The trial had a split-plot with the main

516   plots arranged as a randomised complete block design, with two factors and three replications

517   (Figure 13). The main plot was assigned to the ASC composition and the subplot to the ASC

518   management strategy.

519   Block I   Block II   Block III
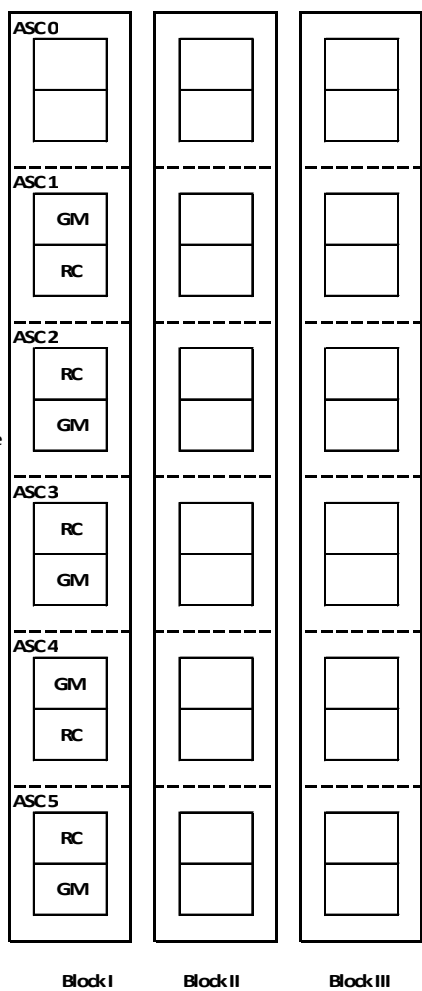
520   **Figure 13.** The FtB experimental design at the Experimental Farm of Metaponto belonging to the Consiglio per la

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.

529   In 2015, ASC compositions were: ASC1 - 100 % cowpea (*Vigna unguiculata* (L.) Walp.),

530   ASC2 - 70 % cowpea + 30 % pearl millet (*Pennisetum glaucum* (L.) R.Br.), ASC3 - 50 %

531   cowpea + 50 % pearl millet, and ASC4 - 40 % cowpea + 30 % pearl millet + 30 % radish

532   (*Raphanus raphanistrum* subsp. *sativus* (L.) Domin). In 2016, ASC compositions were: ASC1 -

533   100 % cowpea, ASC2 - 100 % mung bean (*Vigna radiata* (L.) R.Wilczek), ASC3 - 100 %

534   buckwheat (*Fagopyrum esculentum* Moench), and ASC4 - 35 % cowpea + 35 % mung bean +

535   30 % buckwheat. The cash crop was cauliflower (*Brassica oleracea* var. *botrytis* L.).

536   **Agronomic management**

537   **Field experiment type A**

538   ASCs were sown on November 4th, 2015, and December 29th, 2016. Fertiliser was applied to

539   plots belonging to the fertilisation treatments on April 8th, 2016 and April 26th, 2017 as follows:

540   12 t ha^{-1} of anaerobic digestate from cattle residues in the AD plots and 3.5 t ha^{-1} of commercial

541   organic mineral fertiliser allowed in organic farming in the CO plots (Figure 12). In the T-GM

542   treatments, ASCs were chopped on April 8th, 2016 and April 26th, 2017 and ploughed under and

543   incorporated into the soil by milling on the 18th and 19th of April 2016 and April 28th, 2017. In

544   the NT-RC treatments, the ASCs were flattened by roller crimper on April 15th, 2016 and April

545   26th, 2017. The tomato crop was manually transplanted on April 28th, 2016 and May 5th, 2017,

546   with a row spacing of 1 m and a 0.40 m plant spacing (Picture 17). In the NT-RC system, ASC

547   re-growth was mowed twice on May 10th, and 23rd, 2016. No further weed management was

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 12th of July 2017. The cash crop was drip irrigated weekly.

550   The cash crop harvest was performed from July 7th to August 25th, 2016, and from July 18th to

551   August 25th, 2017.

552

553   **Picture 17.** View of the FtA trial during growth of the cash crop at the Experimental Farm of Metaponto belonging to

554   the Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA) in southern Italy (IT).

555   **Field experiment type B**

556   ASCs were sown on April 21st, 2015 and April 19th, 2016, and were irrigated on emergence.

557   Commercial organic fertiliser (150 kg ha^{-1} N, 450 kg ha^{-1} P$_2$O$_5$, and 150 kg ha^{-1} K$_2$O) was

558   applied just before the ASC termination, whereas in the second year, fertiliser was applied

559   during cash crop development. ASC management was carried out on July 29th, 2015, whereas in

560   the second year, the ASC was terminated by T-GM on July 27th, 2016, and by NT-RC on July

561   28th, 2016.

562   The cauliflower crop was transplanted on August 3rd in both years, with a row spacing of 1.0 m

563   and a 0.45 m plant spacing. During the first year, the NT-RC plots were mowed every two

564   weeks to reduce ASC regrowth biomass, whereas only two weeding operations were carried out

565   in the T-GM plots. During the second year, only two ASC regrowth mowing operations were

566   required, whereas no weed control was carried out in the T-GM plots. The cash crop was

567   irrigated by micro-sprinklers according to crop requirements. The cash crop harvest was

568   performed from November 23rd to December 15th, 2015, and November 28th, 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**

574 The field trial was newly established at the University of Maribor (Pivola), Faculty of

575 Agriculture and Life Sciences (UM), Slovenia (SI) (46° 30' N and 15° 37' E). This trial

576 represented the Alpine South European climatic zone. During the first cycle (2015–2016), the

577 mean annual temperature was 10.9 °C and the mean annual rainfall, 1,009 mm, and during the

578 second cycle (2016–2017) these environmental factors were 11.1 °C and 961 mm, respectively.

579 The trial soil had a loam texture with an average 2.66 % organic carbon content.

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

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

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

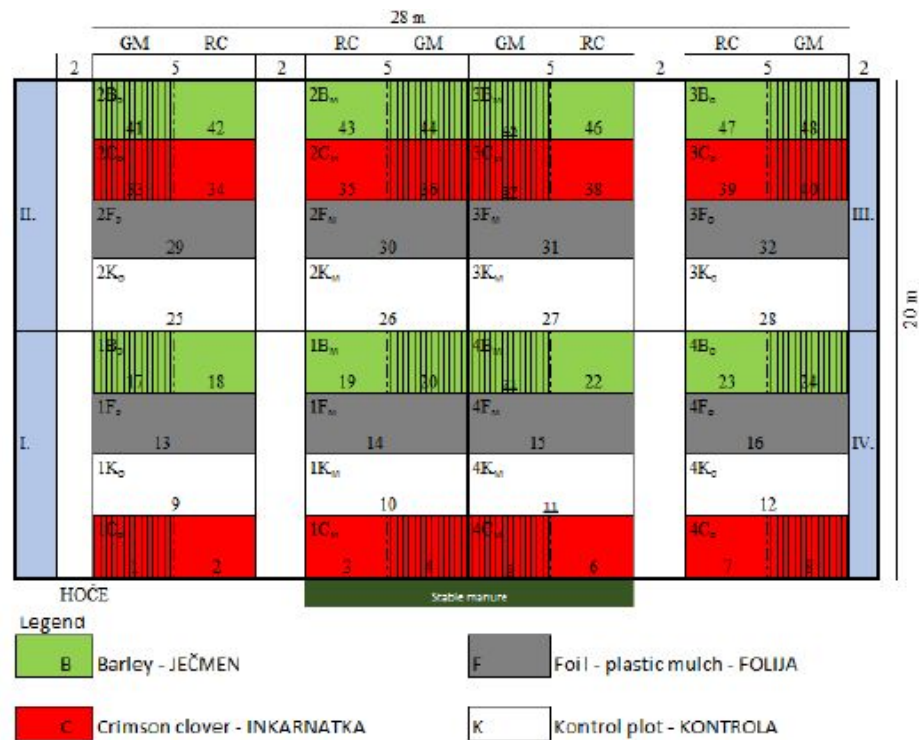583 factors and four repetitions (Figure 14).

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^{-1}) before sowing ASC; and O - Without manure application.

584   The ASC species composition was: 100 % *Hordeum vulgare* (220 kg ha^{-1}), ASC2: - 100 %

585   *Trifolium incarnatum* L. (35 kg ha^{-1}), and two different controls: (1) no ASC and (2) black foil.

586   The two ASC termination strategies were: (1) cover crop terminated with a roller crimper + in-

587   line tillage (NT-RC), and (2) ASC mulched and incorporated into the soil and seedbed prepared

588   with a rotary harrow (T-GM). The roller crimper was 2.5 m wide and weighed 700 kg and was

589   created through co-operation between the Faculty of Agriculture and Life Sciences, Department

590   of Organic Agriculture, Crops, Vegetables and Ornamental Plants and Gorenc d.o.o. from

591   Spodnji Brnik in Slovenia (Picture 18). In the NT-RC plots, furrows for cash crop transplanting

592   were created by in-line tillage (Picture 18). The fertilisation factor had two levels: M application

593 of livestock manure (30 t ha^{-1}) before sowing the ASCs, and O - no manure application. Plot

594 size was 2.5 × 2.5 m. The cash crop was cauliflower (*Brassica oleracea* var. *botrytis* L.).

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**

600 The fertilisation treatment was performed using livestock manure (30 t ha^{-1}) on August 27th,

601 2015 and on August 24th, 2016. ASC1 was sown on August 31st, 2015 and on August 25th, 2016,

602 whereas ASC2 was sown on October 26th, 2015 and October 25th, 2016. The ASCs were

603 managed in the T-GM plots on May 19th, 2016 and on May 20th, 2016 in the NT-RC plots.

604 During the second cycle, all plots were managed on May 18th, 2017.

605 The cauliflower crop was transplanted on June 3rd, 2016, and May 24th, 2017 with a row spacing

606 of 0.6 m and a 0.40 m plant spacing (Picture 19). During the cash crop cycle, all plots were

607 fertilised using commercial organic fertilisers when the cash crop was transplanted

608 (70 kg ha^{-1} N), and during cash crop development (70 kg ha^{-1} N). During the second year, the

609 cash crop was irrigated twice using micro-sprinklers. Weed management was performed

610 manually in all treatments. During the first cycle, three weeding operations were carried out in

611 the T-GM and control plots on June 29th, 2016, July 19th, 2016, and August 11th, 2016. In the

612 NT-RC plots, only one operation was required (August 12th, 2016). During the second cycle,

613 four weeding operations were carried out in the T-GM and control plots (June 19th, 2017, July

614 5th, 2017, July 26th, 2017, and August 17th, 2017), whereas in the NT-RC plots, two operations

615 were required (July 5th, 2017 and August 9th, 2017). The cash crop harvest was performed on

616 September 29th, 2016 and September 5th, 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,

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

References

623 Arlotti, D., Lakkenborg Kristensen, H., Canali, S., De Neve, S., Huyghebaert, B., & Stilmant,

624 D. (2019). Impact of agro-ecological service crops and their termination modes on Soil

625 Mineral Nitrogen dynamic at spring crop implantation. *European Conference on Crop*

626 *Diversification. 18-21 September 2019*. Budapest, Hungary.

627 Arlotti, D., Lakkenborg Kristensen, H., Canali, S., De Neve, S., Sans Serra, F. X., San Martin,

628 G., … Stilmant, D. (2019). Impact of agro-ecological service crops and their termination

629 strategies on soil mineral nitrogen availability, soil humidity, weeds development and

630 cabbage harvest. *X International Scientific Symposium, Farm Machinery and Processes*

631 *Management in Sustainable Agriculture 20-22 November 2019*. Lublin, Poland.

632 Bavec, M., Robačer, M., Bavec, F., Vukmanič, T., Jakop, M., Lisec, U., … Canali, S. (2017).

633 SoilVeg - Improving soil conservation and resource use in organic cropping systems for

634 vegetable production throuhg introduction and management of Agro-ecological Service

635 Crops. *VII South-Eastern Europe Symposium on Vegetables & Potatoes, June 20 - 23,*

636   *2017*. Maribor, Slovenia. Maribor: University of Maribor Press; Pivola: Faculty of
637   Agriculture and Life Sciences.

638   Bavec, M., Robačer, M., Lisec, U., Vukmanič, T., Jakop, M., Grobelnik Mlakar, S., … Canali,
639   S. (2017). Using cover crops for increasing biodiversity and maintaining soil fertility in
640   organic vegetable production. *3rd International Conference Agrobiodiversity "Organic*
641   *Agriculture for Agrobiodiversity Preservation", Novi Sad, 1st - 3rd June 2017*.

642   Hefner, M., Canali, S., Willekens, K., Lootens, P., Deltour, P., Beeckman, A., … Kristensen, H.
643   L. (2020). Termination method and time of agro-ecological service crops influence soil
644   mineral nitrogen, cabbage yield and root growth across five locations in Northern and
645   Western Europe. *European Journal of Agronomy*, *120*, 126144. doi:
646   10.1016/j.eja.2020.126144

647   Hefner, M., Gebremikael, M. T., Canali, S., Sans Serra, F. X., Petersen, K. K., Sorensen, J. N.,
648   … Kristensen, H. L. (2020). Cover crop composition mediates the constraints and benefits
649   of roller-crimping and incorporation in organic white cabbage production. *Agriculture,*
650   *Ecosystems and Environment*, *296*, 106908. doi: 10.1016/j.agee.2020.106908

651   Navarro-Miró, D., Blanco-Moreno, J. M., Ciaccia, C., Chamorro, L., Testani, E., Kristensen, H.
652   L., … Sans, F. X. (2019). Agroecological service crops managed with roller crimper
653   reduce weed density and weed species richness in organic vegetable systems across
654   Europe. *Agronomy for Sustainable Development*, *39*(6), 55. doi: 10.1007/s13593-019-
655   0597-8

656   Navarro-Miró, D., Caballero-López, B., Blanco-Moreno, J., Pérez-Ferrer, A., Depalo, L.,
657   Masetti, A., … Sans, F. (2017). Agro-ecological Service Crops with roller crimper
658   termination enhance ground-dwelling predator communities and pest regulation. In D.
659   Rahmann G, Andres C, Yadav A K, Ardakani R, Babalad H B & W. H. N, Goel S L,
660   Olowe V, Ravisankar N,Saini J P, Soto G (Eds.), *Innovative Research for Organic 3.0 -*
661   *Volume 1: Proceedings of the Scientific Track at the Organic World Congress 2017*
662   *November 9-11* (pp. 416–419). doi: DOI:10.3220/REP1510907717000

663   Navarro-Miró, D., Iocola, I., Persiani, A., Blanco-Moreno, J. M., Kristensen, H. L., Hefner, M.,
664   … Canali, S. (2019). Energy flows in European organic vegetable systems: Effects of the
665   introduction and management of agroecological service crops. *Energy*, *188*, 116096. doi:
666   10.1016/J.ENERGY.2019.116096

667   Tamm, K., Bender, I., Nugis, E., Edesi, L., & Võsa, T. (2018). The impact of the termination
668   technology of agro-ecological service crops on soil properties in open field vegetable
669   production. *Agronomy Research*, *16*(4), 1896–1904. doi: 10.15159/AR.18.152

670   Witvrouw, K. (2016). *Effects of different soil tillage techniques on arthropods and pest control.*
671   *A study to uncover the effects of ASC-termination with a roller crimper*. Ghent University.
672   Masters' dissertation submitted to obtain the degree of Master of Science in Biology

673   Academic year.

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-fall

6   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**

17   The pit-fall station consisted of two pit-fall traps connected with a 10-cm-wide and 1-m- long

18   metal barrier. In both years, two sampling periods (from August–October) of 14 days each were

19   carried out. Pit-fall traps were filled with propylenglycol (40 %). After collection, biological

20   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-

24   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.

28 In FtB, traps were continuously active for the whole growing season, i.e. from early September

29 to the end of December in 2015 and 2016. Traps were checked every three weeks and

30 arthropods were collected four times.

31 **Slovenia (SI)**

32 **Field experiment type A**

33 The pit-fall station consisted of two pit-fall traps connected by a 10-cm-wide and 1-m- long

34 metal barrier. In the first year, five sampling periods (end of June to end of August) of two

35 weeks each were performed. In the second year, there were six sampling periods (beginning of

36 June to end of August) of two weeks each with the exception of the first sampling after 15 days.

37 Pit-fall traps were filled with propylenglycol (40 %). After collection, biological material was

38 rinsed and stored in 70 % alcohol and checked and identified in the laboratory.

39 **Spain (ES)**

40 **Field experiment type B**

41 In Spain, we only studied the activity density of spiders in the FtB trial. The pit-fall station

42 consisted of two pit-fall traps connected by a 10-cm-wide and 1-m-long plexiglas barrier. In the

43 first year, eight sampling periods (from August to December) of 13–18 days each were carried

44 out. In the second year, we carried out seven sampling periods (from September to December)

45 of 12–22 days. Pit-fall traps were filled with propylenglycol (40 %). After collection, biological

46 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 enzyme

50 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 p-

56   nitrophenyl-β-D-glucospyranoside solution was added to one gram of the pre-incubated moist

57   soil. The soil suspensions were incubated for 1 h at 37 °C. After incubation, 1 ml of $CaCl_2$ and 4

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

65   solution and 4 ml of modified universal buffer to two technical replicates of 1 g of sieved soil

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 $CaCl_2$

68   and 4 ml of Tris-buffer pH 12 were added to the samples, which were then filtered immediately

69   using Whatman nº. 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 procedure

76   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**

84   The mineral nitrogen content was assessed using a soil depth of 0.3 m because the dry weather

85   did not allow us to sample more deeply. Six samples were collected per plot area and mixed into

86   one composite sample. Soil mineral nitrogen, measured when the cash crop was harvested, was

87   extracted by 0.5 M KCl (1:5, w/v) and measured by continual flow colourimetry according to

88   QuickChem® Method 12-107-06-3-B and QuickChem® Method 12-107-04-1-B for NH_4^+-N

89   and NO_3^--N, respectively.

90   **Belgium - INAGRO (BE-INAGRO)**

91   **Field experiment type A**

92   Soils were sampled with a hand-driven auger with a 13-mm inner diameter to depths of 0–0.3

93   m, 0.3–0.6 m and 0.6–0.9 m. Four subsamples were taken per plot and combined into one

94   composite sample per soil layer. Soil N_{min} was determined by the extraction of nitrate and

95   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**

98   Soil samples for N leaching were taken to a depth of 2.5 m in November. Ten sub-samples were

99   randomly taken in each subplot by a machine-driven soil piston auger with a 14-mm inner-

100   diameter 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

101   mixed into a composite sample for each depth. Soil samples were frozen until mineral N

102   analysis. After thawing, the subsamples (each 100 g fresh weight) were extracted in 1-M KCl

103   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).

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.

Italy (IT)

114   **Field experiment type A**

115   Soil mineral nitrogen, measured when the cash crop was harvested, was extracted in 2-M KCl

116   (1:10, w/v) and measured using continual flow colourimetry according to Krom (1980) and

117   Henriksen and Selmer-Olsen (1970) for NH_4^+-N and NO_3^--N, respectively. All the soil

118   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 the

122   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^{-1}; 60 °C until constant weight).

129   The minimum diameter of the cabbage head considered as marketable was 130 mm.

Belgium - INAGRO (BE-INAGRO)

Field experiment type A

Cabbage yield at harvest was obtained by hand-harvesting two rows × 2 m. Plant samples were divided into marketable yield; crop residues and fresh and dry weights were calculated.

Denmark (DK)

Field experiment type A

Cabbage marketable yield was assessed by harvesting 16–18 plants (two crop rows × 4.5 m) per plot at harvest (October).

Estonia (EE)

Field experiment type A

In both years, we estimated the cabbage marketable yield by sampling five randomly chosen plants per plot.

Spain (ES)

Field experiment type A

In the first year, we estimated the pepper marketable yield by analysing eight random plants per plot during twelve weekly samplings. In the second year, we assessed five random plants per plot during five biweekly samplings. In both years, we calculated the accumulated yield per plot.

Field experiment type B

In both years, we estimated the cabbage marketable yield by assessing five randomly chosen plants per plot.

France (FR)

Field experiment type A

In both years, we measured the yields of 10 plants per plot × 4 plots per treatment.

Italy (IT)

Field experiment type A

156   At harvest, in the first year, tomatoes were collected from three randomly selected plants (in the

157   centre of the rows in each elementary plot) at three different times in July and August 2016, and

158   marketable and total yields (t ha^{-1}) were recorded. In the second year, tomatoes were collected

159   from three different plants at four different times in July and August 2017, and marketable and

160   total yields (t ha^{-1}) were recorded.

161   **Field experiment type B**

162   At harvest, in both years, cauliflower heads were collected from three randomly selected plants

163   (in the centre of the rows in each elementary plot), and marketable and total yields (t ha^{-1}) were

164   calculated.

165

166   **5. Cash crop quality**

167   The cash crop quality indicator included different measurements of the marketable parameters

168   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^{-1}; 70 °C until constant weight) of marketable heads.

199   **References**

200   Alef, K., & Nannipieri, P. (1995). *Methods in Applied Soil Microbiology and Biochemistry* (A.

201   P. London, Ed.). doi: 10.1016/B978-0-12-513840-6.X5014-9

202   Fornasier, F., & Margon, A. (2007). Bovine serum albumin and Triton X-100 greatly increase

203   phosphomonoesterases and arylsulphatase extraction yield from soil. *Soil Biology and

204   Biochemistry*, *39*(10), 2682–2684. doi: 10.1016/j.soilbio.2007.04.024

205   Henriksen, A., & Selmer-Olsen, A. R. (1970). Automatic methods for determining nitrate and

206   nitrite in water and soil extracts. *The Analyst*, *95*(1130), 514. doi: 10.1039/an9709500514

207   Hutchings, N. J., & Kristensen, I. S. (1995). Modelling mineral nitrogen accumulation in grazed

208   pasture: will more nitrogen leach from fertilized grass than unfertilized grass/clover?

209   *Grass and Forage Science*, *50*(3), 300–313. doi: 10.1111/j.1365-2494.1995.tb02325.x

210   Krom, M. D. (1980). Spectrophotometric determination of ammonia: A study of a modified

211   berthelot reaction using salicylate and dichloroisocyanurate. *The Analyst*, *105*(1249), 305–

212   316. doi: 10.1039/an9800500305

213

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.

| Country | Trial | Termination | Ecological indicators | | | Environmental indicators | | | Agronomic indicators | | | |
			Carabidae AD	Staphylinidae AD	Araneae AD	PRE-EUE	N leaching	Beta-glucosidase	Weed density	Marketable yield	Cash crop quality	M-EUE
BE-CRA-W	FtA	T-GM					4.8 - 8.2		1 - 4	0 - 0.9	59.5 - 144.3	
		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
		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
		NT-RC				0.06 - 0.14	5.8 - 22.5		31 - 101	0 - 0.5	461.6 - 765.2	0 - 0.22
ES	FtA	T-GM				0.13 - 0.18			95 - 1090	2.2 - 3.7	17.1 - 20	0.7 - 1.05
		NT-RC				0.1 - 0.21			0 - 605	2.5 - 4.2	15 - 22	0.81 - 1.31
	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
IT	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
		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
	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^{-1}; BE-INAGRO, DK, EE and IT: mg N kg^{-1}); Beta-glucosidase (BE-INAGRO and

8   DK: μg PNP g^{-1} h^{-1}; IT: nmol 4-MUF g^{-1} h^{-1}). Agronomic indicators: Weed density (individuals m^{-2}); Marketable yield (t ha^{-1}); Cash crop quality (cash crop quality indicator included

9   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.