UNIVERSITAT DE BARCELONA

Gestió dels sistemes hortícoles ecològics a Europa mitjançant la introducció de cultius amb serveis agroecològics i la seva gestió amb el roller crimper

David Navarro Miró

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David Navarro Miró

GESTIÓ DELS SISTEMES HORTÍCOLES ECOLÒGICS A EUROPA MITJANÇANT LA INTRODUCCIÓ DE CULTIUS AMB SERVEIS AGROECOLÒGICS I LA SEVA GESTIÓ AMB EL ROLLER CRIMPER

Facultat de Biologia

Departament de Biologia Evolutiva, Ecologia i Ciències Ambientals

Programa de doctorat de Biodiversitat

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Memòria presentada per David Navarro Miró per optar al grau de doctor per la Universitat de Barcelona

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Salut i agroecologia!

Vila-real, 15 d'octubre de 2020

Abstract

The introduction of agroecological services crops (ASC) in crop rotations is a widely recognised strategy for improving the environmental performance of cropping systems. Nevertheless, several authors have highlighted that the environmental and agronomic performance of ASC depends on the management strategy used to terminate them. Traditionally, European organic farmers have managed ASC as green manure (T-GM). However, in recent years, the use of the roller crimper (NT-RC) for ASC management has attracted the interest of European farmers and researchers, because it flattens the ASC creating a dense layer of plant residue on the soil surface without soil disturbance.

The few studies performed in European vegetable systems, mainly developed in Italy, have analysed the effect of the ASC management by the NT-RC on weed abundance, crop yield and energy balances. Thus, most studies have been conducted under the particular conditions of specific experimental sites, which may have influenced the findings

In order to fill this knowledge gap, this PhD combined results obtained over a two year period from organic vegetable field trials located in different European countries. The support for a common effect of NT-RC across trials was tested by means of a meta-analytic approach based on a weighted version of the Stouffer's method.

Our results indicate that ASC inclusion and management required, on average, a 19.73 % higher energy input investment than systems that did not include them. Nevertheless, ASC management strategies were more prone to increase the energy that potentially could be recycled within the cropping system.

The NT-RC reduced the marketable production efficiency relative to T-GM, but improved the environmental performance by increasing the potential energy that can be recycled within the cropping system. Weed density was reduced under NT-RC by 35.1 % on average in comparison to T-GM. Moreover, we documented a significant reduction of weed species richness under NT-RC, and significant but, in general, minor changes in the weed community composition across the trials. Furthermore, NT-RC enhanced the activity density of ground and rove beetles across different pedo-climatic conditions in Europe. However, NT-RC decreased the cash crop yield and quality, and the activity density of spiders.

Índex

Introducció general

1. Serveis i perjudicis ecosistèmics que proporciona l'agricultura

Els agroecosistemes proporcionen múltiples serveis ecosistèmics indispensables per al benestar humà com la producció d’aliments. Aquests serveis de provisió depenen al seu torn d'una xarxa de serveis de suport i de regulació com són, entre altres, la fertilitat del sòl, el control de plagues i malalties, i la pol·linització. La gestió dels sistemes agrícoles també pot generar perjudicis ecosistèmics que redueixen la producció, com ara l’herbivoria associada a les plagues, generen problemes ambientals, socials i de salut com la contaminació dels aqüífers per la lixiviació de nutrients, i l’aplicació pesticides que afecten el manteniment i el funcionament dels ecosistemes, i al benestar humà (Zhang et al. 2007; Power 2010).

2. Impactes de la gestió convencional dels cultius hortícoles

A Europa, l’1,9 % de la terra cultivable (2,2 milions d’hectàrees) es dedica a cultius hortícoles i produeix al voltant de 65 milions de tones de verdures fresques (De Cicco 2016; EUROSTAT 2019). Els cultius hortícoles són els que requereixen el major consum d’energia (Elsoragaby et al. 2019), la major aportació d’agroquímics (fertilitzants i pesticides) i la taxa de reg més elevada per assegurar els rendiments. La gestió excessivament intensiva d’aquests cultius ha provocat diversos problemes mediambientals a causa de l’elevat consum de recursos no renovables i la lixiviació de nutrients (Torrellas et al. 2012; Min et al. 2012), així com efectes sobre la salut a causa de la presència de residus de pesticides (González-Rodríguez et al. 2008). Per tant, és urgent el disseny de sistemes hortícoles que millorin el funcionament i redueixin els impactes ambientals i socials.

3. L’agricultura ecològica com a sistema alternatiu de gestió

L’agricultura ecològica es va promoure originalment com un sistema holístic de gestió encaminat a millorar la salut del sòl i els aspectes ambientals i socials de la producció agrícola (Seufert et al. 2017). La Federació Internacional d’Agricultura Ecològica (IFOAM) va definir els principis de salut, ecologia, equitat i prevenció, com a base per inspirar el desenvolupament i el creixement de l’agricultura ecològica (Luttikholt 2007).

Segons aquests principis, el disseny dels sistemes agrícoles han de sostenir i millorar la salut dels ecosistemes, els organismes i l'ésser humà mitjançant la preservació de la fertilitat i la salut del sòl, la millora de la biodiversitat i la reducció de la contaminació. A més, el disseny del sistema també ha de reduir la necessitat d’entrades externes mitjançant la millora en la reutilització i el reciclatge d’energia i materials. A més, la gestió de l'agroecosistema ha de mantenir i millorar la qualitat ambiental.

A Europa, l’agricultura ecològica ha rebut el suport de les polítiques de la Unió Europea (UE) des dels anys noranta pels seus potencials beneficis ambientals i sanitaris, i per contribuir als objectius del desenvolupament regional (Padel et al. 1999). El 1991 es va iniciar a la UE la regulació del sector de la producció agroalimentària ecològica amb l'establiment i la normalització de normatives públiques de producció i comercialització de productes ecològics sotmesos a inspecció (Cuéllar-Padilla i Ganuza-Fernandez 2018). Tot i això, l’objectiu principal de la regulació de la UE per a l’agricultura ecològica era l’eliminació de les barreres per al comerç, en lloc de posar l’atenció principal en l’adopció dels principis ambientals, socials i culturals de la producció ecològica (Luttikholt 2007). El resultat d’aquest política explica que les normes i certificacions ecològiques actuals no cobreixen clarament tots els valors bàsics de l’agricultura ecològica definits per IFOAM (Padel 2007; Migliorini i Wezel 2017).

4. Convencionalització dels sistemes ecològics

Segons l’informe de “El món de l’agricultura ecològica. Estadístiques i tendències emergents 2019”, la superfície certificada com a agricultura ecològica ha augmentat de manera exponencial (Helga Willer i Julia Lernoud 2019). El 2017, l’agricultura ecològica certificada representava l’1,4% del total de les terres agrícoles mundials. La demanda de productes ecològics també ha augmentat a nivell mundial i s’espera que continuï creixent. El mercat ecològic mundial va arribar als 97 mil milions de dòlars americans el 2017. Tot i això, l’augment del mercat ecològic mundial ha creat un nou nínxol rentable, que ha atret l’atenció d’actors que segueixen l’actual model agroalimentari convencional (Darnhofer et al. 2010). Aquest procés ha rebut el nom de la convencionalització de l’agricultura ecològica (Buck et al. 1997). Des d’una perspectiva agronòmica, la convencionalització ha comportat la simplificació dels sistemes de cultiu ecològics resultat de l’especialització i la intensificació de la producció (Darnhofer et al. 2010). La convencionalització dels sistemes agrícoles ecològics s’ha basat en un ús intensiu d’energia, una alta pertorbació del sòl i l’aplicació de productes externs a la finca per a la fertilització i la protecció dels cultius (Tittarelli et al. 2017). A més, algunes pràctiques que les agricultores i agricultors ecològics estan duent a terme no són sostenibles, però no estan prohibides explícitament en la normativa de la producció ecològica (Padel 2007). Davant d’aquesta situació, diversos estudis han posat en dubte els beneficis ambientals i la viabilitat agronòmica de l’agricultura ecològica (Trewavas 2001, 2004; Leifeld 2012; Tuomisto et al. 2012; Van Stappen et al. 2015; Seufert et al. 2017), així com han assenyalat les limitacions agronòmiques per a l'aplicació generalitzada de l'agricultura ecològica.

5. Crítiques i limitacions dels sistemes hortícoles ecològics actuals

Les agricultores i agricultors ecològics identifiquen la gestió de la flora arvense com una de les principals limitacions per a la producció hortícola (Turner et al. 2007). A més, la dependència de la pertorbació freqüent del sòl per controlar la flora arvense afecta negativament la sostenibilitat dels sistemes hortícoles ecològics (Trewavas, 2001, 2004). En primer lloc, la llaurada consumeix molta energia i augmenta el consum de combustible fòssil (Alluvione et al. 2011). En segon lloc, llaurar té un impacte directe sobre els organismes del sòl (és a dir, matant-los directament o ferint-los) i el seu hàbitat (Roger-Estrade et al. 2010). Diversos estudis posen de manifest que els caràbids i els estafilínids són sensibles a la pertorbació del sòl (Tamburini et al. 2016; Rivers et al. 2017; Pretorius et al. 2018) i la seva disminució pot tenir conseqüències sobre el control biològic plagues (Tamburini et al., 2016). Finalment, la llaurada intensiva afecta negativament la qualitat biològica del sòl i, per exemple, disminueix l’activitat enzimàtica (avaluada mitjançant l’abundància de l’enzim beta-glucosidasa) que té un paper important en la degradació de la matèria orgànica (Ekenler i Tabatabai, 2003).

Un altre factor limitant important està relacionat amb el menor rendiment dels cultius ecològics respecte dels convencionals (Ponisio et al., 2015). Diversos estudis assenyalen que l’agricultura ecològica és menys eficient ja que requereix més superfície de terra per produir la mateixa quantitat d'aliments que l'agricultura convencional i que es necessita més combustible fòssil per al control de la flora arvense (Trewavas, 2001, 2004). A més, en l'agricultura ecològica, s'ha demostrat que l'adopció d'una gestió del sòl menys intensiva pot reduir el rendiment i la qualitat del cultiu comercial (Ciaccia et al. 2015a; Diacono et al. 2017). A més, alguns estudis afirmen que les estratègies de fertilització basades en l'aplicació de fems animals i l'ús dels adobs verds, així com l'increment del reciclatge d'energia i nutrients dins del sistema de cultiu, poden tindre impactes potencialment negatius sobre el medi ambient a causa del decalatge entre l'alliberament dels nutrients i les necessitats del cultiu (Trewavas, 2001, 2004). La manca de sincronització entre la disponibilitat de nutrients i les necessitats del cultiu pot comportar, a curt termini, la lixiviació de nitrats i l'eutrofització dels cossos d'aigua (Trewavas, 2001) i, a llarg termini, la pèrdua de fertilitat del sòl (Trewavas, 2004). Per aquests motius, cal re-dissenyar els sistemes de cultiu hortícoles ecològics i avaluar-ne la seva sostenibilitat mitjançant un conjunt d'indicadors agronòmics, ambientals i ecològics.

6. Re-disseny de sistemes hortícoles ecològics

El re-disseny dels sistemes de cultiu hortícoles ecològics es refereix a la modificació del sistema o d'una gran part del sistema de cultiu basat en la millora dels processos ecològics en els agroecosistemes (Wezel et al. 2014). Per a això, la introducció de pràctiques agroecològiques pot tenir un paper clau en el re-disseny. Segons Wezel et al. (2014) les pràctiques agroecològiques es defineixen com a pràctiques amb "*l'objectiu de produir quantitats importants d'aliments, que valoritzin de la millor* *manera els processos ecològics i els serveis ecosistèmics per integrar-los com a elements fonamentals en el desenvolupament de les pràctiques*".

6.1 Introducció dels cultius amb serveis agroecològics

La introducció dels cultius que proveeixen serveis agroecològics (a partir d'ara ASC) en la rotació de cultius es una de les estratègies àmpliament reconeguda per millorar la sostenibilitat dels sistemes de cultiu (Wezel et al. 2014; Silva et al. 2017). Aquest terme aplega tots els cultius introduïts en els sistemes agrícoles per proporcionar o promoure serveis ecosistèmics (cultius de captura, cultius de cobertura, cultius complementaris), amb independència de la seva posició en l'esquema rotacional i del mètode emprat per gestionar-los (Canali et al . 2015). En general, els ASC es consideren una estratègia clau per a la gestió de la flora arvense en sistemes ecològics (Gallandt 2014), i el seu ús pot reduir la necessitat d'aportacions externes i disminuir l'ús de recursos no renovables (Schipanski et al. 2014; Robačer et al. 2016). En sistemes hortícoles, els ASC es sembren generalment a les estacions fredes i plujoses. Tot i això, alguns autors també han assenyalat la possibilitat d'establir ASC durant l'estiu a les regions mediterrànies del sud d'Europa, tot i que la seva implementació encara és limitada (Canali et al. 2015).

La introducció dels ASC augmenta la diversitat de cultius i pot disminuir la necessitat de fertilitzants, la lixiviació de nutrients i l'erosió del sòl (Wezel et al. 2014). A més, els ASC redueixen la germinació i l'emergència de la flora arvense (Teasdale et al. 2007). En les produccions hortícoles, els ASC se solen gestionar abans de l'establiment del cultiu comercial per evitar la competència i proporcionar beneficis durant el cicle del cultiu. Tot i això, alguns autors han assenyalat que la tècnica seleccionada per a la gestió dels ASC afecta els serveis subministrats com ara la efectivitat en el control de la flora arvense, l'eficiència energètica i el rendiment del cultiu comercial (Canali et al. 2013; Ciaccia et al. 2016).

6.2 Gestió de cultius amb serveis agroecològics

Entre les agricultores i agricultors ecològics europeus, la tècnica de gestió més estesa consisteix en tallar i picar els ASC i incorporar el material vegetal al sòl mitjançant la llaurada sense inversió de les capes del sòl (encara que de vegades hi ha inversió de les capes del sòl) com a adobs verds (a partir d'ara T-GM), mentre que les tècniques de gestió dels ASC mitjançant la no-llaurada gairebé no s'utilitzen (Peigné et al. 2016). L'adopció limitada de la no-llaurada en el disseny de sistemes ecològics es deu a les importants limitacions relacionades principalment amb la gestió de la flora arvense i el menor rendiment (Pittelkow et al. 2015; Casagrande et al. 2016; Vincent-Caboud et al. 2017). No obstant això, en els darrers anys, l'ús del roller crimper (a partir d'ara NT-RC) per a la gestió dels ASC ha atret l'interès de les persones agricultores i investigadores a tot Europa.

6.3 Ús del roller crimper per a la gestió dels cultius amb serveis agroecològics

L'ús del roller crimper (NT-RC) per a la gestió dels ASC sense utilitzar herbicides es va implementar per primera vegada al Brasil (Kornecki et al. 2009). Posteriorment, el estudis sobre el funcionament del NT-RC i el desenvolupament tecnològic s'han dut a terme principalment a Amèrica Llatina (Altieri et al. 2011; Thomazini et al. 2015), Canadà (Shirtliffe i Johnson 2012) i Amèrica del Nord (Leavitt et al. 2011; Reberg-Horton et al. 2012; Mirsky et al. 2012; Delate et al. 2012; Carr et al. 2013a). Per contra, la investigació i la implementació d'aquesta tecnologia en el context agrícola europeu és encara escàs (Peigné et al. 2007). Mäder i Berner (2012) van suggerir que l'escassa implementació i investigació sobre el NT-RC a Europa podrien estar relacionades amb el clima temperat humit predominant, que dificulta l'adopció de les pràctiques de no-llaurada en agricultura ecològica. En general, la no-llaura implica un menor escalfament del sòl a la primavera, que redueix la mineralització del nitrogen, un menor control de les especies arvenses perennes i una major dificultat per a la incorporació de fems, en comparació a la llaurada del sòl.

El NT-RC consisteix en un cilindre d'acer amb fulles metàl·liques sense tall disposats en un patró de chevron, que aplana els ASC i crea una densa capa de residus vegetals (és a dir, el encoixinat) connectats al sòl per les arrels (Figura 1.a) (Ashford i Reeves 2003).

Figura 1. Roller crimper + llaurada en línea. Detall del roller-crimper (a); eina per a la llaurada en línea (b); tractor equipat amb el roller crimper + eina per a la llaurada en línea (c). Fotos de David Navarro.

La implementació del NT-RC s'ha adreçat principalment a la producció de cereals (Mirsky et al. 2011; Reberg-Horton et al. 2012; Carr et al. 2012, 2013b) i, en una menor mesura, als sistemes hortícoles (Leavitt et al. 2011; Delate et al. 2012). L'escassa adopció d'aquest tècnica en els sistemes de cultiu hortícoles s'explica per la dificultat del trasplantament i la fertilització del cultiu després de l'aixafament i la deposició superficial dels ASC (Luna et al. 2012; Canali et al. 2013).

Per superar aquestes limitacions i facilitar l'adaptació d'aquest disseny de cultiu als sistemes hortícoles ecològics europeus, el NT-RC es va modificar afegint una eina per a la llaurada en línia (Figura 1 b-c) (Canali et al. 2013). Aquesta modificació, basada en discs afilats verticals i una arada vertical disposats en línia a la part posterior del NT-RC, permet aplanar l'ASC i crear simultàniament un solc estret sense modificar l' encoixinat que l'envolta (Figura 2).

Figura 2. Planta de pebrot trasplantada en un solc estret creat pel NT-RC després d'haver aplanat l'ASC al camp experimental de Gallecs. Imatge d'Alejandro Pérez-Ferrer.

6.4 Avantatges i desavantatges de l'ús dels encoixinats

Diversos estudis assenyalen que el re-disseny dels sistemes de cultiu mitjançant l'adopció de pràctiques de no-llaurada per a la gestió dels ASC proporciona beneficis agronòmics, ecològics i ambientals, però també alguns inconvenients. En general, els arguments més comuns a favor del NT-RC són la millora del control de la flora arvense, la reducció dels requeriments energètics i la millora de la salut del sòl, mentre que l'inconvenient principal sol relacionar-se amb el rendiment del cultiu comercial (Canali et al. 2013; Ciaccia et al. 2015b; Diacono et al. 2017).

L'establiment d'una densa capa de residus vegetals a la superfície del sòl (és a dir, l'encoixinat) després d'aplanar l'ASC, redueix dràsticament l'abundància de la flora arvense en comparació amb la incorporació al sòl com a adob verd (Canali et al. 2013; Ciaccia et al. 2015a, 2016). La presència de l'encoixinat redueix la germinació de les llavors de la flora arvense i l'emergència de les plàntules a causa dels canvis que provoca l'encoixinat sobre les condicions ambientals la capa superficial del sòl i la barrera física que dificulta el desenvolupament de les plàntules (Altieri et al. 2011). La modificació de la temperatura mitjana i l'amplitud tèrmica del sòl (Altieri et al. 2011; Canali et al. 2013) i la intensitat de llum que arriba a la superfície del sòl (Teasdale i Mohler 2000) afecten la dormició i la germinació de les llavors (Batlla i Benech-Arnold 2015). A més, la biomassa de l'encoixinat i les condicions climàtiques específiques (temperatura i precipitacions) després de la deposició en superfície del ASC, també afecten la germinació i l'emergència de la flora arvense. En general, la germinació de les llavors i l'emergència de les plàntules disminueix de manera exponencial al augmentar la quantitat de biomassa de l'encoixinat (Teasdale i Mohler 2000). Tot i això, també és important tenir en compte que la quantitat de biomassa dels ASC depèn de les condicions climàtiques específiques de l'any (Carr et al. 2012; Canali et al. 2013).

La llaurada s'identifica generalment com una de les aportacions externes que requereix més energia i, per aquest motiu és necessària l'adopció de tècniques que redueixin la intensitat de la llaurada per millorar el rendiment energètic dels sistemes (Alluvione et al. 2011). Estudis previs realitzats a Itàlia, han destacat que aplanar l’ASC requereix menys consum de combustibles fòssils i menys consum d’energia per a fabricar la maquinària que triturar i incorporar l’ASC al sòl mitjançant la llaurada. A més, la presència de l’encoixinat redueix la mà d'obra emprada durant cultiu comercial, principalment a causa de la disminució de les operacions de desherbat (Canali et al. 2013; Diacono et al. 2017, 2018). Des del punt de vista ecològic, l’adopció d’una gestió de l’ASC sense llaurar redueix l’impacte directe i indirecte de la pertorbació sobre els organismes del sòl, mentre que la presència de l’encoixinat ofereix les condicions favorables per al seu desenvolupament (Sunderland i Samu 2000; Thomson i Hoffmann 2007; Roger-Estrade et al. 2010). A llarg termini, la gestió sense llaurada pot afectar positivament la qualitat física i biològica del sòl (Sapkota et al. 2012).

Pel que fa a la producció agrícola, s’han observat efectes positius i negatius sobre el rendiment del cultiu comercial en els sistemes hortícoles en el que l’ASC es gestiona mitjançant el NT-RC en comparació a sistemes gestionats amb T-GM (Canali et al. 2013; Ciaccia et al. 2016; Diacono et al. 2017). En els casos en el que s’observa una reducció del rendiment i de la qualitat de la producció, alguns estudis assenyalen que aquesta tendència podria estar relacionada amb l’escassetat de nitrogen durant el desenvolupament del cultiu comercial (Ciaccia et al. 2015a; Diacono et al. 2017, 2018).

7. Justificació de la tesi doctoral

Pocs estudis, la major part d'ells realitzats a Itàlia, han analitzat l'efecte de la introducció dels ASC en els fluxos energètics en sistemes hortícoles ecològics en condicions agro-edafo-climàtiques europees. A més d'això, la majoria de les investigacions centrades en aplanar l'ASC s'han centrat principalment en (i) l'optimització del disseny del NT-RC, (ii) la selecció de la millor composició dels ASC, (iii) la identificació dels canvis en l'abundància d'espècies arvenses perennes i (iv) l'anàlisi de l'efecte sobre la producció i la qualitat dels cultius comercials (Mirsky et al. 2012; Carr et al. 2012; Canali et al. 2013; Frasconi et al. 2019). Altrament, des de la implementació del NT-RC per a sistemes hortícoles ecològics, pocs estudis, tots ells realitzats a Itàlia, han analitzat l'efecte de la introducció i la gestió dels ASC mitjançant el NT-RC sobre l'abundància i la diversitat de la flora arvense, el rendiment del cultiu comercial i els balanços d'energia. A més, la majoria d'estudis s'han dut a terme sota les condicions ambientals particulars de llocs experimentals específics (incloent els cultius, el clima i el sòl), que poden haver influït en els resultats. Atès que els patrons agroecològics es poden veure afectats per la naturalesa de l'entorn receptor, la validació de les pràctiques ha de tenir en compte aquesta variabilitat potencial.

Per aquests motius, el coneixement científic actual encara no mostra evidències sòlides dels beneficis des del punt de vista agronòmic, ambiental i ecològic del NT-RC en diferents cultius, sòls i condicions climàtiques en els sistemes hortícoles ecològics europeus. Per tal d'omplir aquest buit de coneixement, aquesta tesi doctoral pretén proporcionar una visió més detallada dels efectes del NT-RC en diferents condicions agro-edafo-climàtiques d'Europa, mitjançant l'anàlisi conjunta de les dades provinents d'experiments paral·lels durant dos anys en diversos països europeus en el marc del projecte SoilVeg (ERA-Net CORE-Organic Plus). Els resultats obtinguts s’estructuren en tres capítols:

- En el primer capítol (Capítol 1. Els cultius amb serveis agroecològics gestionats amb el roller crimper redueixen la densitat i la riquesa de la flora arvense en sistemes hortícoles ecològics a Europa), s’avalua l'efecte de la gestió dels ASC (T-GM vs. NT-RC) sobre els paràmetres estructurals de les comunitats arvenses (és a dir, la densitat i la riquesa específica, i la composició florística). Es va escollir aquesta temàtica perquè, tot i que el NT-RC és una pràctica prometedora per a la gestió de flora arvense, només un estudi s’ha centrat en l’efecte de la gestió del NT-RC en la riquesa d’espècies de flora arvense (Halde et al. 2015), mentre que sols un altre estudi ha descrit, però no analitzat en detall, la seva influència sobre la composició de les comunitats arvenses (Ciaccia et al. 2016).
- En el segon capítol (Capítol 2. Els fluxos d’energia als sistemes hortícoles ecològics europeus: efectes de la introducció i la gestió dels cultius amb serveis agroecològics), s’analitza els efectes de la introducció i la gestió dels ASC (T-GM i NT-RC) sobre els fluxos d’energia del sistema hortícola (és a dir, l’anàlisi de les entrades i sortides d’energia, i l’energia reciclada dins del sistema) en contrast amb l’estratègia de no utilitzar ASC. A més, es va comparar l'eficiència de la producció, els efectes sobre la qualitat dels cultius comercials i l’acompliment ambiental, en termes de fluxos d'energia, entre el NT-RC i el T-GM. Ens hem centrat en aquest tema perquè pocs estudis han analitzat els fluxos d’energia en sistemes hortícoles ecològics. A més, els estudis disponibles no tenen en compte totes les fonts d’energia que es podrien reciclar (és a dir, l’ASC, la flora

arvense, els descarts de la producció i altres residus dels cultius comercials) dins d'un sistema de cultiu i cap d'aquestes investigacions ha avaluat l'eficiència dels sistemes de cultiu per al reciclatge d'energia.

- En el tercer capítol (Capítol 3: Gestió de cultius amb serveis agroecològics en sistemes hortícoles ecològics europeus: La importància d'avaluar aspectes agronòmics, ecològics i ambientals), s'avalua els efectes de la gestió dels ASC (NT-RC vs. T-GM) sobre el sistema de cultiu mitjançant un conjunt d'indicadors agronòmics, ambientals i ecològics, per exemplificar la necessitat d'un anàlisi multidimensional per entendre les implicacions i així poder afrontar els reptes ambientals i agronòmics que se'n deriven. Desenvolupem aquest capítol, ja que la majoria dels estudis disponibles que analitzen NT-RC se centren principalment en aspectes agronòmics i, en menor mesura, en el acompliment ambiental i, cap estudi ha utilitzat un enfocament multidimensional, mitjançant l'avaluació simultània dels aspectes agronòmics, ambientals i ecològics.

Objectius

1. Objectius generals

L’objectiu general de la tesi doctoral és investigar l’efecte de la introducció de cultius amb serveis agroecològics (ASC) i la seva terminació mitjançant la deposició a la superfície del sòl amb el roller crimper (NT-RC) en comparació amb la incorporació al sòl com a adob verd (T-GM) en diferents àrees agrícoles, sòls i condicions climàtiques d’Europa durant dos anys. A aquest efecte, la tesi doctoral se centra en:

- L'avaluació de l'abundància, la diversitat i la composició de la vegetació arvense (Capítol 1) i l'eficiència energètica (Capítol 2) de la gestió dels ASC (NT-RC vs. T-GM).
- L'anàlisi multidimensional dels efectes de la gestió dels ASC (NT-RC vs. T-GM) sobre el sistema hortícola mitjançant un conjunt d'indicadors agronòmics, ambientals i ecològics (Capítol 3).

2. Objectius específics

A continuació s’indiquen els objectius específics de cada capítol de la tesi doctoral.

Capítol 1. Els cultius amb serveis agroecològics gestionats amb el roller crimper redueixen la densitat i la riquesa d'espècies de la flora arvense en sistemes hortícoles ecològics a Europa.

i. Avaluar si la gestió dels ASC (NT-RC vs. T-GM) afecta l’estructura de les comunitats arvenses (és a dir, la densitat i la riquesa d'espècies, i la composició florística) en diferents àrees agrícoles, sòls i condicions climàtiques d’Europa.

ii. Valorar la magnitud dels efectes de la gestió dels ASC (NT-RC vs. T-GM), i si aquest efecte és consistent o, al contrari, depèn de les variacions de les condicions agronòmiques i ambientals del cultiu i de la biomassa produïda pels ASC.

Capítol 2. Els fluxos d'energia als sistemes hortícoles ecològics europeus: efectes de la introducció i la gestió dels cultius amb serveis agroecològics

i. Quantificar els canvis en les entrades i sortides d'energia (eliminada i reciclada dins del sistema) en relació amb la introducció i gestió dels ASC en comparació amb una estratègia que no els utilitzi (sòl nu, a partir d'ara BS), en un ampli ventall de condicions pedo-climàtiques.

ii. Comparar l'eficiència en la producció, la qualitat del cultiu comercial i el comportament ambiental, en relació als fluxos d'energia, entre la gestió dels ASC (NT-RC vs. T-GM) a Europa.

Capítol 3: Gestió de cultius amb serveis agroecològics en sistemes hortícoles ecològics europeus: La importància d'avaluar aspectes agronòmics, ecològics i ambientals

Aquest capítol té com a objectiu avaluar els efectes de la gestió dels ASC (NT-RC vs. T-GM) sobre el funcionament del sistema hortícola mitjançant un conjunt d'indicadors agronòmics, ambientals i ecològics, per exemplificar la necessitat d'un anàlisi multidimensional per entendre les conseqüències de la gestió agrícola i així poder afrontar els reptes agronòmics, ambientals i ecològics que se'n deriven.

i. Analitzar l’efecte de la gestió dels ASC (NT-RC vs. T-GM) mitjançant l’avaluació de l'efecte sobre la fauna dels artròpodes del sòl, l'activitat dels enzims del sòl, el potencial de lixiviació de nitrogen i el potencial de reciclatge d’energia dins del sistema de cultiu.

ii. Avaluar el comportament agronòmic de la gestió dels ASC (NT-RC vs. T GM) mitjançant l'anàlisi del rendiment i la qualitat dels cultius comercials, l'eficiència energètica de la producció i el control de la flora arvense.

Informe del director de tesi del factor d’impacte dels articles publicats

Informe del director de la tesi doctoral del factor d'impacte de les publicacions presentades

El Dr. F. Xavier Sans i Serra, director de la tesi doctoral del Sr. David Navarro Miró presenta el següent informe sobre el factor d'impacte de les publicacions que formen part de la present memòria.

Capítol 1

Títol: Agroecological service crops managed with roller crimper reduce weed density and weed species richness in organic vegetable systems across Europe

Autors: David Navarro-Miró, José M. Blanco-Moreno, Corrado Ciaccia, Lourdes Chamorro, Elena Testani, Hanne Lakkenborg Kristensen, Margita Hefner, Kalvi Tamm, Ingrid Bender, Manfred Jakop, Martina Bavec, Hélène Védie, Līga Lepse, Stefano Canali, F. Xavier Sans

Publicació: Agronomy for Sustainable Development (2019) 39:55, https://doi.org/10.1007/s13593-019-0597-8

Factor d'impacte (2019): 4.531

Posició dins l'àrea:	Agronomy 4/91 (primer decil i primer quartil)
	Gea and Sustainable Science and Technology 15/41 (segon quartil)

Capítol 2

Títol: Energy flows in European organic vegetable systems: effects of the introduction and management of agroecological service crops

Autors: David Navarro-Miro, Ileana Iocola, Alessandro Persiani, José M. Blanco-Moreno, Hanne Lakkenborg Kristensen, Margita Hefner, Kalvi Tamm, Ingrid Bender, Hélène Védie, Koen Willekens, Mariangela Diacono, Francesco Montemurro, F. Xavier Sans, Stefano Canali

Publicació: Energy 188 (2019) 116096, https://doi.org/10.1016/j.energy.2019.116096

Factor d'impacte (2019): 6.082

Posició dins l'àrea: Thermodynamics 3/61 (primer decil i primer quartil)
Energy and Fuels 20/112 (primer quartil)

Capítol 3

Títol: Managing agroecological service crops in European organic vegetable systems: The need of evaluating agronomic, ecological and environmental performance

Autors: David Navarro-Miró[1*], José M. Blanco-Moreno[1], Corrado Ciaccia[2], Elena Testani[2], Ileana Iocola[2], Laura Depalo[3], Giovanni Burgio[3], Hanne Lakkenborg Kristensen[4], Margita Hefner[4], Kalvi Tamm[5], Ingrid Bender[5], Alessandro Persiani[6], Mariangela Diacono[6], Francesco Montemurro[7], Koen Willekens[8], Hélène Védie[9], Martina Bavec[10], Martina Robačer[10], Donatienne Arlotti[11], Pauline Deltour[12], Stefaan De Neve[13], Mesfin Tsegaye Gebremikael[13], Lourdes Chamorro[1], Berta Caballero-López[14], Alejandro Pérez-Ferrer[1], Stefano Canali[2], F. Xavier Sans

Després de una primera revisió per part del comitè editorial de la revista Journal of Applied Ecology, la nova versió de l'article ha estat enviada el 29 de setembre

Factor d'impacte (2019): 5.840

Posició dins l'àrea: Ecology 15/168 (primer decil i quartil)
Biodiversity Conservation 4/59 (primer decil i primer quartil)

Tots els articles que formen part de la Tesi doctoral del Sr. David Navarro Miró han estat sotmesos per a la seva publicació a revistes científiques d'àmbit internacional que consten al Science Citation Index (SCI).

Barcelona, 28 de setembre de 2020

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UNIVERSITAT DE BARCELONA
Facultat de Biologia
Departament de Biologia Evolutiva,
Ecologia i Ciències Ambientals

Informe del director de la tesi doctoral sobre la participació del doctorand en les publicacions

El Dr. F. Xavier Sans i Serra, director de la tesi doctoral del Sr. David Navarro Miró, presenta el següent informe sobre la contribució del doctorand en cadascuna de les publicacions presentades en la present memòria.

Capítol 1

Agroecological service crops managed with roller crimper reduce weed density and weed species richness in organic vegetable systems across Europe

David Navarro-Miró, José M. Blanco-Moreno, Corrado Ciaccia, Lourdes Chamorro, Elena Testani, Hanne Lakkenborg Kristensen, Margita Hefner, Kalvi Tamm, Ingrid Bender, Manfred Jakop, Martina Bavec, Hélène Védie, Līga Lepse, Stefano Canali, F. Xavier Sans

El doctorant ha contribuït en el disseny dels treball, ha recopilat, harmonitzat i analitzat les dades obtingudes pels diversos equips de recerca implicat en l'estudi, ha participat en la interpretació dels resultats i ha redactar l'article. També s'ha encarregat de l'establiment, la gestió i la recol·lecció de mostres dels experiments FtA i FtB al Parc de l'Espai d'Interès Natural de Gallecs.

Capítol 2

Energy flows in European organic vegetable systems: effects of the introduction and management of agroecological service crops

David Navarro-Miro, Ileana Iocola, Alessandro Persiani, José M. Blanco-Moreno, Hanne Lakkenborg Kristensen, Margita Hefner, Kalvi Tamm, Ingrid Bender, Hélène Védie, Koen Willekens, Mariangela Diacono, Francesco Montemurro, F. Xavier Sans, Stefano Canali

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Capítol 3

Managing agroecological service crops in European organic vegetable systems: The need of evaluating agronomic, ecological and environmental performance

David Navarro-Miró[1*], José M. Blanco-Moreno[1], Corrado Ciaccia[2], Elena Testani[2], Ileana Iocola[2], Laura Depalo[3], Giovanni Burgio[3], Hanne Lakkenborg Kristensen[4], Margita Hefner[4], Kalvi Tamm[5], Ingrid Bender[5], Alessandro Persiani[6], Mariangela Diacono[6], Francesco Montemurro[7], Koen Willekens[8], Hélène Védie[9], Martina Bavec[10], Martina Robačer[10], Donatienne Arlotti[11], Pauline Deltour[12], Stefaan De Neve[13], Mesfin Tsegaye Gebremikael[13], Lourdes Chamorro[1], Berta Caballero-López[14], Alejandro Pérez-Ferrer[1], Stefano Canali[2], F. Xavier Sans

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Finalment, certifico que cap dels coautors dels articles abans esmentats ha utilitzat de manera implícita o explícita aquests treballs per a l'elaboració d'una altra tesi doctoral.

Barcelona, 9 d'octubre de 2020

UNIVERSITAT DE BARCELONA
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Metodologia general

Aquesta tesi doctoral s’emmarca en el projecte europeu SoilVeg (ERA-Net CORE-Organic Plus) (http://projects.au.dk/coreorganicplus/researchprojects/ solveg /). Aquest projecte de recerca tenia com a objectiu verificar la hipòtesi que l’ús del roller crimper per a la gestió dels ASC (NT-RC) manté el rendiment i la qualitat dels cultius hortícoles (i), millora la qualitat del sòl i l’ús dels nutrients dins del sistema (ii), redueix el consum de combustibles fòssils (iii) i crea un entorn supressiu per a plagues, malalties i la flora arvense (iv). El projecte també va analitzar la hipòtesi que la gestió dels ASC mitjançant NT-RC redueix les pèrdues de nutrients del sistema sòl/planta i les emissions de gasos d’efecte hivernacle respecte de la incorporació al sòl com a adobs verds. A més, el projecte també pretenia verificar si la introducció i la gestió dels ASC durant la temporada càlida a les zones climàtiques més suaus (és a dir, les regions del sud d’Europa) podrien ser una opció factible per al disseny i la gestió dels sistemes hortícoles.

Amb aquesta finalitat, es van establir camps experimentals de cultius hortícoles ecològics a Bèlgica (BE), Dinamarca (DK), Estònia (EE), França (FR), Itàlia (IT), Eslovènia (SI) i Espanya (ES) durant dos anys. A BE, es van dur a terme tres experiments a diferents llocs del país (BE-ILVO, BE INAGRO i BE-CRA-W). Les ubicacions incloses en aquest estudi van cobrir diferents zones climàtiques (Metzger et al. 2005) i textures del sòl per a la producció hortícola a Europa (Taula 1, pàgina 29).

En aquest projecte es van establir dos tipus experiments paral·lels. Tots els socis van realitzar l'experiment del tipus A (a partir d’ara FtA). El FtA va consistir en introduir els ASC en la estació amb més pluges i/o més freda i, després de la seva gestió, es van trasplantar cultius hortícoles de primavera-estiu. El primer cicle FtA va tenir lloc durant

Taula 1. Clima general, temperatura mitjana i pluviometria anual durant l’experimentació, i tipus de sòl per a cada experiment. També s’indica el cultiu comercial, la composició de l’ASC, el disseny experimental i els factors analitzats. FtA: cultiu comercial primavera-estiu; FtB: cultiu comercial tardor-hivern. Les zones climàtiques europees es refereixen a la classificació de Metzger et al. (2005). BE: Bèlgica; DK: Dinamarca, EE: Estònia, ES: Espanya; FR: França; IT: Itàlia i SI: Eslovènia. 1Y: primer any, 2Y: segon any d’experimentació. Composició ASC: L: lleguminoses; G: gramínies; B: crucíferes. Variables explicatives: T: Terminació; B: biomassa total; Y: Any; F: Fertilització; A: Composició ASC. Disseny experimental: 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.

País	Experiment	Zones climàtiques	Temperatura i pluviometria (mitjana anual)	Tipus de sòl	Cultiu comercial	Composició de l'ASC	Variables explicatives	Disseny experimental	Repeticions per tractament
BE-CRA-W	FtA	Atlàntic central	1Y: 10.99 °C; 538 mm	Franco llimós	Col llombarda	L i/o G	T; B	S-P	Quatre
BE-ILVO	FtA	Atlàntic central	1Y: 11.1 °C; 898 mm 2Y: 11.3 °C; 822 mm	Franco arenós	Col	L i G	T; B; Y	SS-P	Quatre
BE-INAGRO	FtA	Atlàntic central	1Y: 11.0 °C; 860 mm 2Y: 11.3 °C; 697 mm	Franco arenós	Col	L i/o G	T; Y; A	S-P	Quatre
DK	FtA	Atlàntic nord	1Y: 9.3 °C; 614 mm 2Y: 9.1 °C; 673 mm	Franco arenós	Col	L i/o G	T; B; Y	S-P	Tres
EE	FtA	Nemoral	1Y: 6.0 °C; 825 mm 2Y: 5.8 °C; 694 mm	Franco argilo-sorrenc	Col	L or G	T; B; Y; F	ST-P	Tres
ES	FtA	Mediterrani Nord	1Y: 16.5 °C; 406 mm 2Y: 16.1 °C; 409 mm	Argilós	Pebrot verd	L i/o G	T; B; Y	R-S-P	Quatre
	FtB	Mediterrani Nord	1Y: 16.1 °C; 344 mm 2Y: 16.5 °C; 406 mm	Argilós	Col de Milán	L i/o G	T; B; Y	R-S-P	Quatre
FR	FtA	Mediterrani Nord	1Y: 15,5 °C; 521 mm 2Y: 15.3 °C; 558 mm	Franco argilós	Carbassa “Butternut”	L i/o G	T; B; Y	R-S-P	Tres
IT	FtA	Mediterrani Nord	1Y: 16.7 °C; 539 mm 2Y: 16.5 °C; 402 mm	Argilós	Tomàquet	L i G	T; B; Y; F	SS-P	Tres
	FtB	Mediterrani Nord	1Y: 16.6 °C; 470 mm 2Y: 16.7 °C; 539 mm	Argilós	Coliflor	L i/o G i B	T; B; Y	SS-P	Tres
SI	FtA	Alpí sud	1Y: 10.9 °C; 1009 mm 2Y: 11.1 °C; 961 mm	Llimós	Coliflor	L or G	T; B; Y; F	SS-P	Quatre

el 2015 i el 2016 i el segon, durant el 2016 i el 2017. En paral·lel, l'experiment del tipus B (a partir d'ara FtB) es va localitzar exclusivament a IT i ES. A l'experiment FtB, les condicions mediterrànies van permetre la introducció dels ASC a la estació seca i càlida (és a dir, estiu) amb reg de suport i, després de la seva terminació, la plantació d'un cultiu comercial de tardor-hivern. El primer cicle FtB va tenir lloc durant el 2014 i el 2015 i el segon, durant el 2015 i el 2016.

Tots els experiments es van dur a termes durant dos anys consecutius. L'experiment es va repetir en les mateixes parcel·les en els dos anys a ES i BE-ILVO, mentre que en els altres països la parcel·la experimental es va traslladar a zones adjacents del mateix camp seguint un disseny rotacional previst per al segon any d'experimentació. Cada experiment tenia diferents condicions climàtiques, textura del sòl, composició dels ASC, gestió i disseny experimental (Taula 1, pàgina 29). No obstant això, la comparació entre les dues estratègies de gestió dels ASC va ser comuna a tots els experiments. La gestió NT-RC consistia en aplanar l'ASC mitjançant diverses passades (2-4 passades) amb el roller crimper per tal d'obtenir una capa de residus vegetals (encoixinat) i posteriorment crear un solc estret per facilitar el transplantament del cultiu comercial sense pertorbar l'encoixinat que l'envolta, mitjançant una operació més lenta amb la llaurada en línia. L'aparell per a dur a terme la llaurada en línia es va incorporar a la part posterior del roller crimper en tots els experiments excepte en DK i FR, on es va utilitzar en una passada independent amb el tractor. La gestió de T-GM consistia en segar-triturar l'ASC, incorporar el material vegetal al sòl mitjançant la llaurada i la preparació del llit de sembra. A l'apèndix 1 (pàgines 164-205) es proporciona més informació sobre el disseny experimental i la gestió agronòmica de cadascun desl experiments en cultius hortícoles ecològics.

Les activitats del projecte es van organitzar en set paquets de treball (WP). Els líders dels WP van dur a terme la selecció de procediments de mostreig i la gestió bàsica dels conjunts de dades (és a dir, la recollida, el procés bàsic ordenació de les dades, etc.).

La informació recopilada pel projecte es va utilitzar en la present tesi doctoral per investigar l'efecte de la gestió del ASC en el funcionament dels sistemes hortícoles ecològics, mitjançant l'estudi experimental en diferents cultius, sòls i condicions climàtiques a Europa. A continuació, es va ajustar un model estadístic per a cada experiment i mesura, i es va utilitzar un enfocament meta analític per combinar els *P-valors* i analitzar l'efecte de l'estratègia de gestió per a cada indicador a través dels experiments (Zaykin 2011).

En aquest capítol, en primer lloc, es descriu de manera detallada el disseny, la gestió i la recollida de mostres dels experiments FtA i FtB que es van establir a l'Espai d'Interès Natural de Gallecs (Barcelona, Espanya) per part del Grup de Recerca en Agroecologia de la Universitat de Barcelona. La informació que es facilita pretén exemplificar com van ser es protocols experimentals duts a terme pels altres participants del projecte SoilVeg a Europa. En segon lloc, es descriu per a cada capítol de la tesi doctoral la metodologia específica i les anàlisis estadístiques realitzades per assolir els objectius establerts.

1. Camp experimental de Gallecs

El Parc de l'Espai d'Interès Natural de Gallecs (Barcelona, Espanya) és una zona rural de 753 hectàrees situada a 15 quilòmetres al nord de Barcelona (41° 33'42 "N 2° 12' 7" E). El clima és mediterrani pre-costaner, amb una temperatura mitjana anual i precipitacions de 14,5 ºC i 602 mm respectivament, i el sòl és típicament calcari.

Els experiments van ser establerts pel Grup de Recerca en Agroecologia de la Universitat de Barcelona en un camp amb gestió ecològica des del 2005. El cultiu anterior a l'establiment dels experiments va ser blat. La textura del sòl era franca i la proporció mitjana de carboni orgànic era del 0,95 %. El contingut mitjà de nitrogen-Nítric (N-NO_3) era de 37,19 mg kg^{-1} i de nitrogen total 0,12 % (mètode Kjeldahl), valors entre mitjans i alts. El contingut mitjà de fòsfor (P, mètode Olsen) era alt (29,21 mg kg^{-1}).

El disseny experimental del FtA i FtB va ser un "strip-plot" aleatori amb dos factors (la composició i la gestió de l'ASC) i quatre rèpliques (Figura 3). Els diferents tractaments es van distribuir aleatòriament en bandes paral·leles separades per 2 m de distància i es van delimitar quatre rèpliques de 6 m × 4 m dins de cada banda. El disseny experimental va ser condicionat, en gran mesura, per la necessitat de realitzar totes les operacions agrícoles en la mateixa direcció i facilitar el trànsit de maquinària entre parcel·les.

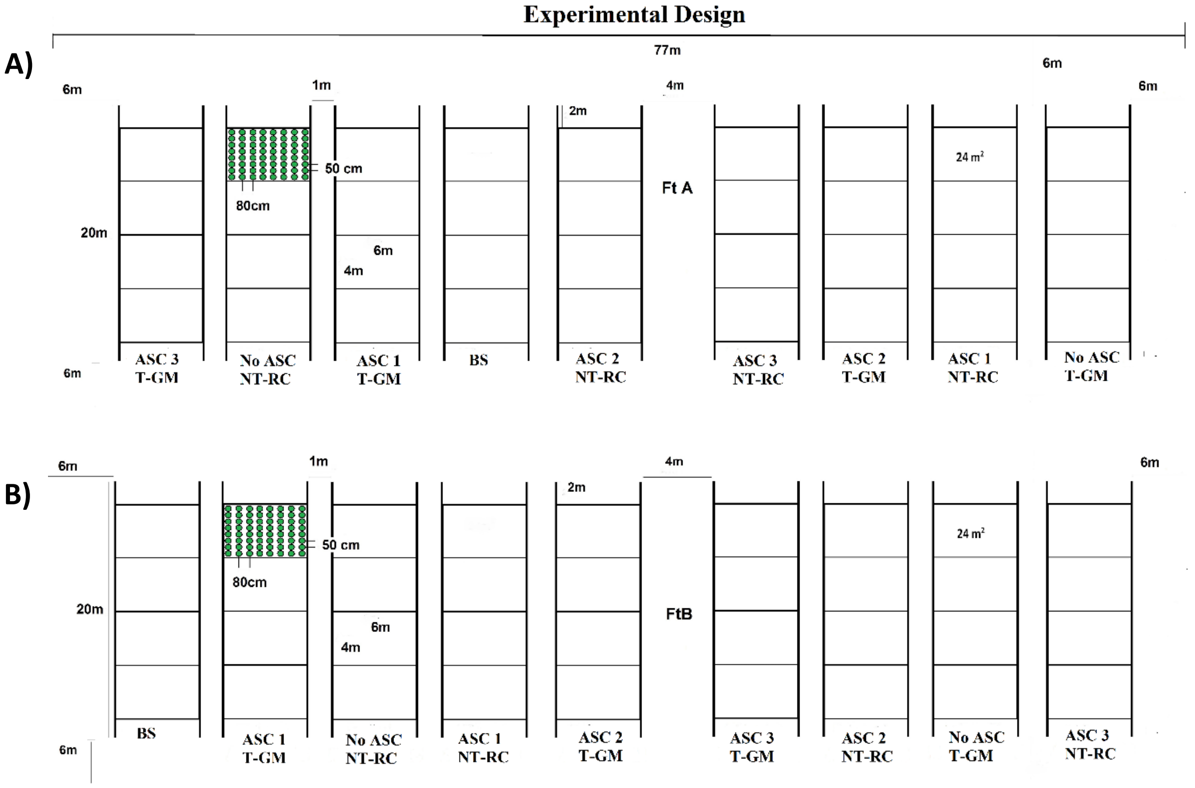

Figura 3. Disseny dels experiments FtA i FtB en el camp del Parc de l'Espai d'Interès Natural de Gallecs. El disseny experimental del FtA i del FtB va resultar de la combinació de dos factors, el tipus d'ASC i la seva gestió. NT-RC: ASC aplanat i dipositat sobre la superfície del sòl amb el roller crimper; T-GM: ASC picat, triturat i incorporat al sòl com a adob verd amb la llaurada; BS: sòl nu, tractament sense ASC. A) Disseny experimental FtA: ASC 1- 100 % barreja de cereals (80,94 % *Avena byzantina* K. Koch i 19,06 % *Hordeum vulgare* L.); ASC 2- 70 % barreja de cereals + 30 % *Vicia sativa* L.; ASC 3- 50% barreja de cereals + 50% *Vicia sativa* i No ASC - vegetació arvense espontània. B) Disseny experimental FtB: ASC 1- 100 % *Vigna unguiculata* (L.) Walp.; ASC 2- 70 % *V. unguiculata* + 30 % *Sorghum bicolor* (L.) Moench; ASC 3- 50 % *V. unguiculata* + 50 % *S. bicolor*; No ASC: vegetació arvense espontània.

1.1 Tractaments

Els factors principals del disseny experimental dels dos estudis paral·lels (FtA i FtB) van ser la composició de l'ASC i el tipus de gestió. La gestió dels ASC corresponia a dos tipus de estratègies de terminació. La gestió amb el roller crimper (NT-RC) que consistia en: i) aplanar l'ASC amb diverses passades de roller crimper per obtenir un encoixinat de residus vegetals, i ii) crear un solc de trasplantament estret sense pertorbar el mantell que l'envolta, mitjançant una operació més lenta amb la llaurada en línia. La gestió mitjançant adobs verds (T-GM) consistia en: i) tallar i picar l'ASC; ii) incorporar l'ASC al sòl mitjançant la llaurada, i iii) preparar el llit de sembra. Addicionalment, es va establir un tractament de control sense coberta del sòl (sòl nu, BS) que consistia en eliminar la vegetació espontània regularment.

La composició de l'ASC va ser específica per a cada estudi. En l'experiment FtA, la composició dels ASC va ser: i) 100 % barreja de cereals (80,94 % *Avena byzantina* K. Koch i 19,06% *Hordeum vulgare* L.) (200 kg ha^{-1}) (ASC 1); ii) 70 % barreja de cereals (140 kg ha^{-1}) + 30 % *Vicia sativa* L. (75 kg ha^{-1}) (ASC 2); iii) 50 % barreja de cereals (100 kg ha^{-1}) + 50 % *Vicia sativa* (125 kg ha^{-1}) (ASC 3) i iv) vegetació espontània (No ASC). El segon any es van eliminar els tractaments ASC 2 i No ASC.

En l'experiment FtB, el primer factor incloïa quatre tipus d'ASC: i) 100 % *Vigna unguiculata* (L.) Walp. (192 kg ha^{-1}) (ASC 1); ii) 70 % *V. unguiculata* (134,4 kg ha^{-1}) + 30 % *Sorghum bicolor* (L.) Moench (9 kg ha^{-1}) (ASC 2); iii) 50 % *V. unguiculata* (96 kg ha^{-1}) + 50 % *S. bicolor* (13,6 kg ha^{-1}) (ASC 3) i iv) vegetació espontània (No ASC). El segon any la densitat de sembra de l'ASC es va incrementar un 30 % en tots els tractaments amb ASC.

1.2 Gestió dels experiments FtA i FtB en el Gallecs Trial

A l'experiment FtA el cultiu comercial va ser el pebrot verd (*Capsicum annuum* L. var. Dulce Italiano) i es va trasplantar el 26 de maig de 2016 i el 20 de juny de 2017. L'última collita del pebrot va ser el 3 d'octubre de 2016 i el 2 d'octubre de 2017.

Taula 2. Relació de les operacions agronòmiques realitzades durant el cultiu del pebrot en l'experiment FtA. S'indiquen les dates durant els dos cicles experimentals en les parcel·les amb l'ASC depositat sobre la superfície del sòl mitjançant el roller crimper (NT-RC) i en les parcel·les amb l'ASC incorporat al sòl amb la llaurada (T-GM).

Operacions agronòmiques	Dates			
	NT-RC		T-GM	
	Primer cicle	Segon cicle	Primer cicle	Segon cicle
Llaurada vertical amb l'arada de cisells	17/11/2015	14/12/2016	17/11/2015	14/12/2016
Preparació del llit de sembra i sembra dels ASC	19/11/2015	09/01/2017	19/11/2015	09/01/2017
Aixafar l'ASC mitjançant el roller crimper	04/05/2016	18/05/2017		
Triturat de l'ASC			04/05/2016	18/05/2017
Incorporació de l'ASC com a adob verd amb l'arada de cisells			18-19/05/2016	01-02/06/2017
Roller crimper + llaurada en línia	24/05/2016	13/06/2017		
Trasplantament manual del pebrot	26/05/2016	20/06/2017	26/05/2016	20/06/2017
Fertilització manual del pebrot	27/05/2016	21/06/2017	27/05/2016	21/06/2017
Desherbat manual	Del 01/07/2016 al ; 22/08/2016, cada dos setmanes	12,27/07/2017; 09/08/2017	Del 20/06/2016 al 22/08/2016, cada 2 setmanes	12,27/07/2017; 09/08/2017
Collita del pebrot	del 18/07/2016 al 03/10/2016 setmanalment	del 21/08/2017 al 02/10/2017 cada 15 dies	del 18/07/2016 al 03/10/2016 setmanalment	del 21/08/2017 al 02/10/2017 cada 15 dies
Trituració residus del pebrot	18/11/2016	11-12/10/2017	18/11/2016	11-12/10/2017

Taula 3. Relació de les operacions agronòmiques realitzades durant el cultiu de la col en l'experiment FtB. S'indiquen les dates durant els dos cicles experimentals en les parcel·les amb l'ASC depositat sobre la del sòl mitjançant el roller crimper (NT-RC) i en les parcel·les amb l'ASC incorporat al sòl amb la llaurada (T-GM).

Operacions agronòmiques	**Dates**			
	NT-RC		**T-GM**	
	Primer cicle	**Segon cicle**	**Primer cicle**	**Segon cicle**
Cultivador superficial per a l'eliminació de la flora arvense		18/04/2016		18/04/2016
Preparació del llit de sembra amb rotativa		20/04/2016		20/04/2016
Llaurada vertical amb l'arada de cisells	30/04/2015		30/04/2015	
Preparació del llit de sembra i sembra de l'ASC	30/04/2015	04/05/2016	30/04/2015	04/05/2016
Reg de l'ASC	7/05/2015 - 15/07/2015	10/06/2016 - 18/08/2016	7/05/2015 - 15/07/2015	10/06/2016 - 18/08/2016
Aixafar l'ASC mitjançant el roller crimper	23,27/07/2015	26/08/2016		
Triturat de l'ASC			23/07/2015	26/08/2016
Incorporació de l'ASC com a adob verd amb l'arada de cisells + preparació del llit de sembra			28/07/2015	05-06/09/2016
Roller crimper + llaurada en línia	29/07/2015	06/09/2016		
Trasplantament manual de la col	04/08/2015	13/09/2016	04/08/2015	13/09/2016
Fertilització manual de la col	04/08/2015	20/09/2016	04/08/2015	20/09/2016
Desherbat manual	25/08/2015; 07/09/2015	18 -19 /10/2016	07/09/2015	18 -19 /10/2016
Collita de col	30/11/2015 i 2/12/2015	22/02/2016	30/11/2015 i 2/12/2015	22/02/2016
Trituració residus de la cols	15/03/2016	18/03/2016	15/03/2016	18/03/2016

A l'experiment FtB el cultiu comercial va ser la col de Milan (*Brassica oleracea* L. var. Sabauda) i es va trasplantar el 4 d'agost de 2015 i el 20 de setembre de 2016. L'última collita de col de Milan es va dur a terme el 2 de desembre de 2015 i el 22 de febrer de 2017. A l'experiment FtA, la fertilització es va realitzar just després del trasplantament amb un fertilitzant orgànic comercial (170 kg ha^{-1} N). A l'experiment FtB, en els dos anys la quantitat de fertilitzant va ser la mateixa (100 kg ha^{-1} N), però el primer any la fertilització es va dividir en dues aplicacions (és a dir, una just després del trasplantament i l'altra durant el desenvolupament de la col), mentre que el segon any només es va dur a terme una fertilització just després del trasplantament. A l'experiment FtB, l'ASC es va regar amb aspersors els dos anys, mentre que la col es va regar segons les necessitats del cultiu mitjançant reg per degoteig. A l'experiment FtA, només es va regar el cultiu comercial segons les necessitats del cultiu, mitjançant reg per degoteig. Les operacions agronòmiques es detallen a la Taula 2 (pàgina 35) per FtA i la Taula 3 (pàgina 36) per a FtB.

1.3 Mostrejos

1.3.1 Abundància de la flora arvense i dels cultius amb serveis agroecològics

Recobriment i biomassa de les flora arvense i de l'ASC durant el període de l'ASC

El recobriment i la biomassa de la flora arvense es va avaluar abans de la terminació de l'ASC (Taula 2, pàgina 35; i Taula 3, pàgina 36). El percentatge de recobriment total i el percentatge de recobriment de cada espècie tant d'ASC com de la flora arvense es va avaluar de manera visual en mostres d'1 m x 1 m que es van establir de manera aleatòria dins de cadascun dels quatre quadrants en que es va dividir cadascuna de les parcel·les. Per a l'avaluació de la biomassa es va recol·lectar la biomassa aèria d'una submostra de 50 cm x 50 cm dins de cadascun dels quadrats emprats per l'estudi del recobriment de la vegetació. La flora arvense i la biomassa de l'ASC van ser separades i emmagatzemades en bosses de paper. El material es va assecar a l'estufa durant 72 hores a 70 °C per obtenir el pes sec.

Densitat de flora arvense durant el període de cultiu comercial

La densitat de la flora arvense es va avaluar immediatament abans de la primera operació de desherbat (Taula 2, pàgina 35; i Taula 3, pàgina 36). Es van establir dues mostres de 25 cm × 40 cm per quadrant a cadascuna de les parcel·les. Les mostres es van col·locar en relació amb la línia de cultiu comercial, de manera que a la cantonada de cada mostra es va mantenir una planta del cultiu comercial i el costat més llarg es va col·locar perpendicularment a la línia de transplantament. A més, per tal d'evitar l'efecte del mostreig de la biomassa de l'ASC, no es van recol·lectar mostres a les zones d'influència d'extracció de la biomassa (Figura 4). A cada mostra, es va comptabilitzar el nombre d'individus de cada espècie arvense i es va indicar el seu origen (plàntula germinada o rebrot de planta establerta).

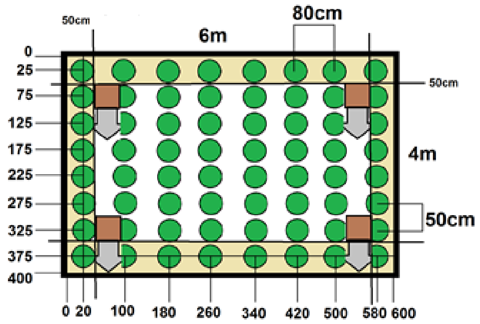

Figura 4. Disseny del mostreig. S'indica la zona central de 15 m^2 (5 m × 3 m) on s'han realitzat avaluacions per evitar l'efecte de vora (blanc) i la disposició del cultiu comercial (cercles verds). El quadrat marró representa la zona on es va avaluar la biomassa de la flora arvense i de l'ASC. La fletxa indica l'àrea d'influència d'eliminació de la biomassa, on no es van realitzar més avaluacions.

1.3.2 Abundància dels artròpodes del sòl

Al Gallecs Trial, el mostreig d’artròpodes del sòl només es va realitzar durant el cultiu comercial a l’experiment FtB. Es va establir una estació de caiguda “pit-fall” al centre de cada parcel·la per tal d’evitar l’efecte marge. L'estació de caiguda estava formada per dues trampes de caiguda separades per una petita paret de metacrilat de 1 m x 0,2 m. Les trampes de caiguda es van omplir amb propilenglicol (40 %). Després de cada recol·lecció, es va esbandir el material biològic i es va emmagatzemar en alcohol al 70 %. Els espècimens recol·lectats es van identificar al laboratori a nivell d’ordre. Al primer cicle, el mostreig es va dur a terme des del 04/08/2015 fins al 02/12/2015, i les trampes van estar activades de mitjana 15 dies amb un rang que va variar entre 13 i 18 dies. Al segon cicle, el mostreig es va dur a terme des del 15/09/2016 fins al 09/01/2017, i les trampes van estar activades de mitjana 15 dies amb un rang que va variar entre 12 i 22 dies.

1.3.3 Rendiment i qualitat del cultiu comercial

A l’experiment FtA, el primer any, es va avaluar el rendiment comercial del pebrot mitjançant el seguiment de vuit plantes seleccionades de manera aleatòria per parcel·la durant dotze mostrejos setmanals. El segon any, es va fer el seguiment de cinc plantes aleatòries per parcel·la durant cinc mostrejos quinzenals. Durant els dos anys, s’ha calculat el rendiment acumulat per parcel·la. El primer any, l’estimació de la qualitat de la collita comercial va tenir en compte la longitud de de cada pebrot a partir de la collita de vuit plantes aleatòries per parcel·la durant dotze mostrejos setmanals. El segon any, el procediment va ser el mateix, excepte que es van avaluar cinc plantes aleatòries per parcel·la durant cinc mostrejos quinzenals.

A l’experiment FtB, els dos anys d’experimentació, es va estimar el rendiment comercialitzable de la col mitjançant l’anàlisi de cinc plantes aleatòries per parcel·la. L’avaluació de la qualitat de la col va tenir en compte el diàmetre de la inflorescència de cinc plantes aleatòries per parcel·la.

1.3.4 Paràmetres per a l’anàlisi energètica

Les dades sobre les entrades i sortides d’energia es van recollir a partir del cicle del cultiu, tenint en compte el període del cultiu de l’ASC i del cultiu comercial, per a cada estratègia de gestió de l’ASC i any. L’entrada d’energia va incloure l’energia associada a la mà d’obra, el consum de gasoil, l’electricitat, l’aigua per a reg, les llavors de l’ASC, el planter del cultiu comercial, les esmenes orgàniques per al sòl (és a dir, fems i compost comercial), les aportacions externes per a la protecció de cultius (és a dir, insecticides, coure i sofre), i la fracció energètica de la maquinària, estimada en base al pes de la maquinària i de la vida útil.

La sortida d’energia va tenir en compte l’energia associada al rendiment de cultiu comercial que compleix els estàndards de qualitat comercials basats en l’aparença externa, el rendiment del cultiu no comercialitzable, els residus de cultiu comercial i la biomassa total de l’ASC (és a dir, l’ASC i flora arvense associada). L’ASC i la biomassa de flora arvense es van mesurar just abans de la gestió de l’ASC.

El capítol "3.2 Càlcul de les entrades i sortides d'energia" (pàgina 47) recull la descripció més detallada de l'estimació de les entrades i sortides d'energia.

2. Material i mètodes del capítol 1

2.1 Experiments implicats

Els experiments hortícoles ecològics implicats en aquest capítol es van localitzar a Dinamarca (DK), Estònia (EE), Itàlia (IT), Eslovènia (SI) i Espanya (ES).

2.2 Procediment de mostreig i tractament de dades

Cada grup de recerca que formava part del projecte va avaluar l’abundància de la flora arvense i de les espècies de l’ASC en una fase inicial del cultiu comercial. Tant els individus provinents de la germinació de les llavors com els rebrots de plantes establertes es van comptar i identificar a nivell d'espècie abans de les operacions de desherbat. Aquestes dades proporcionaven mesures de la densitat i la riquesa d'espècies de la flora arvense.

La densitat de flora arvense (individus m^{-2}) va comprendre el nombre total d’individus germinats i rebrotats, incloses les espècies de la flora arvense i l’ASC, per tenir en compte tota la competència potencial envers els cultius comercials. D'altra banda, la riquesa d'espècies de flora arvense (nombre d'espècies/mostra) i la composició florística es refereixen exclusivament a la flora arvense germinada al començament del cultiu comercial. En aquests casos, es va analitzar exclusivament la flora arvense germinada per analitzar específicament la resposta de les comunitats arvenses als diferents mètodes de gestió de l’ASC.

La densitat de flora arvense i l’ASC es va calcular fent una mitjana per a cada parcel·la en tots els experiments, excepte a ES on es van tenir en compte les ubicacions exactes de les mostres (vegeu més avall). La riquesa d'espècies arvenses no es pot estandarditzar per una superfície fixa i, per tant, en cada experiment fa referència a l'àrea de mostreig.

2.3 Anàlisis estadístiques

Cada experiment es va realitzar sota les seves pròpies condicions pedo-climàtiques i disseny experimental. La informació específica sobre les condicions ambientals (és a dir, la temperatura mitjana anual i les precipitacions, la textura del sòl), el cultiu comercial cultivat i la composició dels ASC de cadascun dels experiments es detallen a la Taula 1 (pàgina 29). El rang de variació de la biomassa seca total, la proporció de flora arvense de la biomassa total i el procediment de mostreig de la flora arvense (és a dir, el nombre de mostres per parcel·la) i la seva distribució temporal (és a dir, dies després del trasplantament) d'aquest estudi es detallen a la Taula 4 (pàgina 43).

Per aquest motiu, en lloc d'agrupar les dades de tots els experiments, es va decidir desenvolupar un model estadístic per a cada experiment que incloïa totes les variables experimentals (Taula 1, pàgina 29) per descomptar el seu efecte sobre la variable depenent. Només la terminació (T-GM i NT-RC), any (any 1 i any 2) i la biomassa seca total van ser variables explicatives comunes a tots els experiments. Les dos primeres es van incloure com a factors, mentre que la biomassa es va incloure com a covariable. Tenint en compte les característiques específiques de cada experiment, l'any resumeix les variacions de les condicions de cultiu causades per variacions interanuals de les temperatures i les precipitacions, i la temporització i l'eficàcia de les operacions agronòmiques, així com les diferències en relació amb el canvi de parcel·la seguint la

Taula 4. Biomassa màxima i mínima de l'ASC abans de la seva terminació i proporció de la biomassa que corresponia a les espècies arvenses que hi van créixer per a cadascun dels experiments i anys de mostratge. També s'indica el moment del mostratge, i el nombre i la mida de les mostres emprades a cadascun dels experiments. 1Y: primer any, 2Y: segon any d'experimentació.

País	Experiment	Rang de biomassa seca ($t\ ha^{-1}$ ASC + flora arvense)	Proporció de flora arvense en la biomassa total (%)	Mostreig de flora arvense (mostres per parcel·la)	Distribució temporal del mostreig (dies després del trasplantament)
Dinamarca	FtA	1Y: 2.32 - 6.74	1Y: 7.66 ± 1.14	Quatre mostres de 0,25 m^2	1Y: 26 dies
		2Y: 0.12 - 9.32	2Y: 28.98 ± 7.05		2Y: 22 dies
Estònia	FtA	1Y: 3.84 - 11.20	1Y: 1.98 ± 0.51	Quatre mostres de 0,25 m^2	1Y: 69 dies
		2Y: 2.28 - 11.54	2Y: 1.07 ± 0.09		2Y: 37 dies
Itàlia	FtA	1Y: 2.73 - 12.41	1Y: 1.29 ± 0.54	Quatre mostres de 0,0625 m^2	1Y: 47 dies
		2Y: 1.85 - 8.74	2Y: 0.96 ± 0.25		2Y: 57 dies
	FtB	1Y: 2.29 - 6.29	1Y: 19.02 ± 2.43	Quatre mostres de 0,0625 m^2	1Y: 28 dies
		2Y: 1.60 - 5.44	2Y: 20.72 ± 3.16		2Y: 30 dies
Eslovènia	FtA	1Y: 4.80 - 11.20	1Y: 22.54 ± 1.91	Dues mostres de 0,25 m^2	1Y: 43 dies
		2Y: 2.51 - 11.43	2Y: 31.24 ± 1.96		2Y: 29 dies
Espanya	FtA	1Y: 7.16 - 12.13	1Y: 0.21 ± 0.04	Vuit mostres de 0,1 m^2	1Y: 21 dies
		2Y: 5.04 - 18.55	2Y: 0.33 ± 0.06		2Y: 22 dies
	FtB	1Y: 2.92 - 16.35	1Y: 70.89 ± 3.4	Vuit mostres de 0,1 m^2	1Y: 30 dies
		2Y: 0.98 - 19.23	2Y: 63.95 ± 4.01		2Y: 36 dies

rotació de cultius, dins del camp experimental. La biomassa seca total inclou la biomassa dels diferents ASC i la flora arvense present abans de la gestió de l'ASC.

A DK, EE, IT i SI, es van utilitzar models lineals d'efectes mixtes per a cada experiment i any. La disposició experimental específica, descrita a la secció anterior, va definir la selecció dels efectes aleatoris per a cada camp experimental. A ES, la necessitat de facilitar el trànsit de maquinària entre parcel·les va condicionar el disseny experimental. Així, es van introduir estructures de correlació espacial en els models d'ES per tenir en compte la manca d'independència entre mostres (Pinheiro i Bates 2000). Es van comparar models que inclouen les diferents classes d'estructures de correlació espacial i un model sense estructura de correlació espacial mitjançant proves de relació de probabilitats i criteris d'informació d'Akaike (AIC) per establir el millor model per a cada variable depenent i any.

Quan era necessari, les dades es van transformar per satisfer els requisits de normalitat i homoscedasticitat. La densitat de flora arvense es va transformar aplicant logaritmes i mitjançant arrels quadrades. La riquesa d’espècies de flora arvense es va transformar aplicant logaritmes. Totes les anàlisis estadístiques es van realitzar amb el programa R (R Core Team, 2018); per als models lineals d’efecte mixt, vam utilitzar la funció `lme` del paquet R `nlme` (Pinheiro et al. 2017), mentre que per als models ES amb estructures de correlació espacial, hem utilitzat la funció `gls`.

L’enfocament meta-analític es va aplicar per analitzar l'efecte, de manera conjunta pels diversos països, de la gestió del ASC sobre la densitat i la riquesa de la flora arvense. Aquest enfocament meta-analític pot ser gairebé tan potent com el basat en la combinació de les dades (Zaykin 2011). Hem utilitzat la prova Z ponderada, que és essencialment una versió ponderada del mètode de Stouffer:

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

on $Z_i = \Phi^{-1}(1 - p_i)$; p_i és el *P*-valor de l'estudi i de *k* estudis en total; w_i és el pes seleccionat per a l'estudi; i Φ i Φ^{-1} són la funció de distribució acumulativa normal estàndard i la seva inversa, respectivament. Per a aquest estudi, hem ponderat *Zi* mitjançant la mida de l'efecte normalitzat, tal com suggereix Zaykin (2011):

$$w_i = \frac{|\mu_i|}{SE_i}$$

on μ_i és l'estimació del coeficient i SE_i és el seu error estàndard. Per provar la mateixa hipòtesi alternativa, els *P*-valors individuals es van convertir a un costat per combinar-se de la manera següent (Zaykin 2011):

$$p_{one-sided} = \begin{cases} \frac{p_{two-sided}}{2}, \text{si la direcció de l'efecte coincideix amb la hipòtesi alternativa} \\ 1 - \frac{p_{two-sided}}{2}, \text{alternativament.} \end{cases}$$

La independència entre els *P*-valors és necessària per a la prova Z ponderada. Així, vam agrupar les dades dels dos anys consecutius per analitzar l'efecte de la gestió en cada experiment.

Els canvis en la composició de les comunitats arvenses es van analitzar mitjançant l'anàlisi permutacional multivariant de la variància (PERMANOVA). Abans de la PERMANOVA, vam realitzar els passos suggerits per Anderson (2001): i) transformar les mesures d'abundància de flora arvense en dades de presència/absència; ii) utilitzar la distància Jaccard per calcular les distàncies entre parcel·les; i iii) provar l'homogeneïtat en la dispersió multivariada amb la funció `betadisper` del paquet de R `vegan` (Oksanen et al. 2017). L'anàlisi PERMANOVA es va realitzar amb la funció `adonis` amb el paquet de R `vegan` (Oksanen et al. 2017); aquesta funció descompon la variància de les matrius de distàncies i atribueix els components de la variància (és a dir, mesurada com a parcial R^2) a les variables explicatives (és a dir, factors i covariable).

També es va calcular la importància relativa de la mida de l'efecte de la biomassa seca total (ASCs + flora arvense), any i gestió de l'ASC. Per a la densitat i la riquesa de la flora arvense, el coeficient estimat per a cada variable explicativa es va dividir per l'*intercept* del model (Armengot et al. 2015), mentre que per a la composició de la comunitat arvense, la mida de l'efecte estava relacionada amb la R^2 parcial de cada variable per cada experiment (Koricheva et al. 2013).

3. Material i mètodes del capítol 2

3.1 Experiments implicats

Els experiments hortícoles ecològics implicats en aquest capítol es van realitzar a Bèlgica (BE-ILVO), Dinamarca (DK), Estònia (EE), França (FR), Itàlia (IT) i Espanya (ES).

3.2 Càlcul de les entrades i sortides d'energia

La caracterització de les operacions agronòmiques realitzades a cadascun dels experiments ha estat essencial per al càlcul de les entrades i sortides d'energia (Taula 5, pàgina 48). L'ús energètic dels diferents sistemes s'ha estimat multiplicant cada entrada/sortida pel seu corresponent coeficient d'energia equivalent, extret de la literatura (Taula 6, pàgina 49). El consum de gasoil del tractor per a cada operació específica es va mesurar segons el procediment suggerit per Canali et al. (2013). L'ús de combustibles fòssils, estimat a partir de les equivalències de la Taula 6 (pàgina 49), va tenir en compte el consum de gasoil i els costos del lubricant (Mandal et al. 2002). Els inputs d'energia per a la fabricació dels tractors i les maquinàries es van calcular mitjançant la fórmula següent (Mohammadi i Omid 2010):

$$\mathrm{ME} = \frac{\mathrm{E} \times \mathrm{G}}{\mathrm{T}} \; (1)$$

on *ME* és l'energia de la maquinària (MJ h^{-1}), *E* és l'energia estimada de producció d'una màquina (E = 62,7 MJ kg^{-1}), *G* és el pes de la màquina (kg) i *T* és la vida útil de la màquina (h). La vida útil de tractors i maquinària es va obtenir de diverses fonts (ASAE 2000; Alluvione et al. 2011; Özgöz et al. 2017).

Taula 5. Caracterització de les operacions agronòmiques realitzades en cada experiment. FtA: cultiu comercial primavera-estiu; FtB: cultiu comercial tardor-hivern. 1Y: primer any, 2Y: segon any d'experimentació. 2WD: Tractor amb tracció a les dues rodes; 4WD: tractor amb tracció a les quatre rodes ASC: Cultius amb serveis agroecològics. RC: Roller crimper. NT-RC: RC + llaurada en línia. RH: motocultor. MW: segadora.

País	Preparació del sòl	Reg de l'ASC	Terminació adob verd	Terminació roller Crimper	Plantació	Reg	Desherbat	Fertilització	Collita	Protecció del cultiu	Gestió dels residus del cultiu
Bèlgica (ILVO)	Cultivador per a l'aplicació de fems + arada de cisells	No	2 WD + MW 2 WD + arada de cisells	2 WD + RC 2 WD + NT-RC	Màquina plantadora	1Y: No hi ha reg 2Y: 2 regs manualment	Mecànic + Manual	Fertilitzadora	Manual	*Bacillus thuringiensis*	Fet mulch amb MW
Dinamarca	Arada	No	2 WD + MW 2 WD + RH	2 WD + RC 2 WD + NT-RC	Màquina plantadora	1Y: 2 vegades per aspersor 2Y: no hi ha reg	Desbrossadora	Fertilitzadora	Manual	Red + *Bacillus thuringiensis*	MW + llaurada
Estònia	Aplicació de fems + llaurar	No	2 WD + MW 2 WD + llaurada	2 WD + RC (2-4 vegades) 2 WD + NT-RC	Manual	1Y: No hi ha reg 2Y: 1 reg manual	Manual	Mecànica	Manual		MW + llaurada
França	Subsolador + RH	No	2 WD + MW 2 WD + RH	2 WD + RC 2 WD + NT-RC	Manual	Reg per degoteig	Manual	Esparcidor d'adobs	Manual		MW + llaurada
Itàlia	Arada	FtA: No FtB: Si	4 WD + MW 4 WD + RH	4 WD + RC 4 WD + NT-RC	Manual	Reg per degoteig setmanal	Manual	Manual	Manual	FtA: Cobre + piretre	MW + llaurada
Espanya	Arada de cisells	FtA: No FtB: Si	4 WD + MW 4 WD + RH	4 WD + RC 4 WD + NT-RC	Manual	Reg per degoteig setmanal	Manual	Manual	Manual		MW + llaurada

Taula 6. Equivalents energètics de les entrades i sortides d'energia dels sistemes de cultiu ecològics analitzats. S'indica per a cadascun dels valors utilitzats la referència bibliogràfica emprada en aquest estudi.

Entrades i sortides d'energia	Unitats	Equivalents d'energia (unitat MJ^{-1})	Referències
Entrada			
Treball humà	h	1.96	(Mandal et al. 2002)
Aigua per a reg	m^3	0.63	(Özgöz et al. 2017)
Fems	kg	0.3	(Mandal et al. 2002)
Compost	kg	1.908	(Pergola et al. 2018)
Dièsel	L	56.31	(Mandal et al. 2002)
Electricitat	kWh	11.93	(Mohammadi and Omid 2010)
Llavors dels ASC	kg	14.7	(Baran and Gokdogan 2014)
Planter del cultiu comercial	unit	0.2	(Bojacá and Schrevens 2010)
Protecció del cultiu			
Insecticides	kg	237	(Deike et al. 2008)
Coure	kg	78.2	(Spugnoli et al. 1993)
Sofre	kg	7.1	(Spugnoli et al. 1993)
Sortida			
Cultiu comercial			
Pebrot	t ha^{-1}	837.36	(U.S. Department of Agriculture 2019)
Carbassa	t ha^{-1}	1884.06	(U.S. Department of Agriculture 2019)
Col	t ha^{-1}	1130.436	(U.S. Department of Agriculture 2019)
Tomàquets	t ha^{-1}	753.624	(U.S. Department of Agriculture 2019)
Coliflor	t ha^{-1}	1046.7	(U.S. Department of Agriculture 2019)
Biomassa de l'ASC	kg	0.3	(Spugnoli et al. 1993)
Residus del cultiu comercial	kg	0.3	(Spugnoli et al. 1993)

Les aportacions d'energia procedents de les esmenes orgàniques del sòl (fems, compost orgànic, etc.), les llavors dels ASC, el planter del cultiu hortícola, la mà d'obra i l'aigua per al reg es van classificar com a aportacions d'energia renovable (RE), mentre que les aportacions d'energia no renovable (NRE) van incloure la maquinària, els combustibles fòssils, els productes per a la protecció del cultiu i l'electricitat (Mohammadi i Omid 2010; Unakıtan i Aydın 2018). No obstant això, es va considerar que la fertilització mitjançant adobs orgànics compostats industrials va representar el

6,8% dels ingressos d’energia no renovable a causa de la fabricació industrial i els processos d’embalatge (Alonso i Guzmán 2010).

L’estudi energètic de les diferents estratègies de gestió es va dur a terme tenint en compte i) el rendiment del cultiu hortícola comercial (MCY) (MJ ha^{-1}), definit com el rendiment del cultiu hortícola que compleix els estàndards de qualitat comercials basats en l’aspecte extern; i ii) l’energia potencialment reciclable (PRE) (MJ ha^{-1}), que compren el rendiment del cultiu hortícola no comercialitzable, els residus del cultiu i la biomassa total de l’ASC (és a dir, l’ASC i la flora arvense).

3.3 Paràmetres per avaluar l’acompliment energètic

Per aprofundir en les diferències en l´ús de l’energia de les dues estratègies de gestió de l’ASC (NT-RC i T-GM), es va calcular l’eficiència en l’ús d’energia (EUE) i l’energia neta (NE) segons les fórmules següents (Barut et al. 2011):

$$\mathrm{EUE} = \mathrm{Sortides\ d'energia\ (MJ\ ha^{-1})/\ Entrades\ d'energia\ \ (MJ\ ha^{-1})}\ (2)$$

$$\mathrm{NE\ (MJ\ ha^{-1}) = Sortides\ d'energia(MJ\ ha^{-1}) - Entrades\ d'energia\ (MJ\ ha^{-1})}\ (3)$$

Aquests indicadors d’eficiència energètica quantifiquen l’eficiència d’un sistema agronòmic en la transformació d’entrades en sortides (Özgöz et al. 2017). En el nostre estudi, es va calcular l’EUE i el NE considerant les entrades d’energia com: i) MCY (MJ ha^{-1}) i ii) PRE (MJ ha^{-1}).

També es va comparar l’acompliment energètic en funció de la qualitat del rendiment del cultiu comercial en termes d’energia. Per aquest motiu, es va proposar l'indicador energètic de la producció comercialitzable del cultiu (MER), que es calcula com la relació entre el rendiment comercialitzable del cultiu comercial (MJ ha^{-1}) i el rendiment total del cultiu comercial (MJ ha^{-1}):

$$\text{MER} = \text{Rendiment comercialitzable (MJ ha}^{-1}\text{)/ Rendiment total (MJ ha}^{-1}\text{)} \quad (4)$$

A més, proposem l'indicador del potencial de reciclatge energètic (ERR), que quantifica l'energia potencialment reciclable per unitat de rendiment comercialitzable del cultiu comercial:

$$\text{ERR} = \frac{\text{Energia potencialment reciclable (MJ ha}^{-1}\text{)}}{\text{Rendiment comercialitzable (MJ ha}^{-1}\text{)}} \quad (5)$$

3.4 Anàlisis estadístiques

3.4.1 Anàlisi dels components principals per avaluar els ingressos i sortides d'energia

L'anàlisi de components principals (PCA en anglès) es va realitzar per explorar les similituds i diferències en les entrades i sortides d'energia entre NT-RC, T-GM i BS. La PCA es va realitzar mitjançant el paquet d'anàlisi de dades multivariant `FactoMineR` (Lê et al. 2008) del llenguatge de programació estadística R (R Core Team, 2016), i es va utilitzar el paquet `Factoextra` (Kassambara i Mundt 2017) per visualitzar els resultats.

Les diferències en les entrades d'energia entre els experiments (per exemple l'electricitat o les aportacions externes per a la protecció dels cultius) va comportar la necessitat d'agregar les entrades en tres variables en la PCA: i) el consum total d'energia (TE); ii) el consum d'energia renovable (RE) i iii) el consum d'energia no renovable (NRE). Per a la quantificació de les variables de sortida d'energia del sistema es va considerar MCY com a sortides que eren extretes del sistema, mentre que PRE quantificava les sortides d'energia reciclades dins del sistema. Les dades es van escalar a la variació d'unitat abans de l'anàlisi per evitar que les variables amb valors alts dominessin.

3.4.2 Enfocament meta-analític per comparar els paràmetres d'acompliment energètic entre el roller crimper i l'adob verd

Els índex d'acompliment energètic es van utilitzar per comparar les dues estratègies de gestió de l'ASC. A aquest efecte, de la mateixa manera que en els capítols anteriors, es va fer servir un enfocament meta-analític (Zaykin 2011) per provar un efecte comú del NT-RC (en comparació amb T-GM) en els índexs d'eficiència energètica entre els diversos experiments. Per obtenir més detalls sobre l'enfocament meta-analític, consulteu la secció anterior "2.3 Anàlisis estadístiques" (pàgina 42) de "2. Material i mètodes del capítol 1 ".

4. Material i mètodes del capítol 3

4.1 Experiments implicats

En aquest capítol es combina els resultats dels experiments de cultius hortícoles ecològics situats a set països – Bèlgica (BE), Dinamarca (DK), Estònia (EE), França (FR), Itàlia (IT), Eslovènia (SI) i Espanya (ES) – realitzats durant dos anys com a part del projecte SoilVeg. A BE, es van establir tres experiments diferents a tot el país (BE-ILVO, BE-INAGRO i BE-CRA-W). Per tant, es van analitzar els resultats de vint-i-dos conjunts de dades originals (és a dir, onze experiments de camp, incloent FtA i FtB, de dos anys).

4.2 Indicadors per a l'avaluació multifuncional de la gestió dels cultius amb serveis agroecològics

En aquest capítol es va utilitzar un conjunt d'indicadors ecològics, ambientals i agronòmics per a l'avaluació multifuncional de les estratègies de gestió dels ASC (NT-RC i T-GM). A més d'un conjunt d'indicadors comuns avaluats en tots els experiments, vam seleccionar una sèrie d'indicadors específics que es van utilitzar d'acord amb els objectius i condicions dels diferents experiments.

4.2.1. Indicadors ecològics i ambientals

Es va investigar els efectes de la gestió dels ASC sobre el sòl mitjançant l'anàlisi del seu impacte sobre la fauna dels artròpodes i l'activitat enzimàtica del sòl. Es va seguir el concepte d'indicadors ecològics *sensu* McGeoch (1998), ja que les funcions que representen aquests indicadors són d'un gran interès per a l'agricultura (Niemelä, 2000). Es va avaluar l'impacte de la gestió dels ASC sobre la fauna del sòl mitjançant l'avaluació de la densitat en activitat dels caràbids (Carabidae), dels estafilínids (Staphylinidae) i de les aranyes (Araneae). S'ha demostrat que aquests tàxons del sòl són sensibles a les pràctiques agrícoles (incloent la llaurada i l'encoixinat) i s'utilitzen sovint per exemplificar l'efecte de les pràctiques agrícoles sobre els organismes que viuen a la superfície del sòl (Döring i Kromp 2003; Rivers et al. 2017; Pizzolotto et al. 2018; Pretorius et al. 2018). En cada experiment, es va calcular la densitat en activitat (a partir d'ara AD) dels artròpodes del sòl com la mitjana de l'abundància de cada grup taxonòmic en tots els mostrejos dividits pel nombre de trampes i el nombre de dies en que les trampes van estar en funcionament. La AD obtinguda es va normalitzar a set dies:

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

on *n* és l'abundància total de cada taxó, *T* és el nombre de trampes i *d* és el nombre de dies que les trampes van estar en funcionament.

Addicionalment, es va avaluar l'efecte de la gestió dels ASC sobre l'activitat dels enzims del sòl mitjançant l'activitat de l'enzim beta-glucosidasa, que s'ha demostrat que és sensible a la intensitat de la llaurada del sòl (independentment de les condicions pedo-climàtiques) i, per tant, pot proporcionar informació ràpida sobre els canvis en les propietats del sòl (Ekenler i Tabatabai, 2003; Knight i Dick, 2004).

En els experiments FtA, es va mesurar el nitrogen mineral del sòl quan es va collir el cultiu comercial com a indicador del potencial de lixiviació de nitrogen (N lixiviació). Segons Hutchings i Kristensen (1995), al final de la temporada de creixement –que coincideix amb l'inici de la temporada de lixiviació– es pot suposar que el nitrogen mineral del sòl restant es lixiviarà durant l'hivern. El potencial de reciclatge de materials i energia dins del sistema de cultiu es va calcular utilitzant l'energia potencialment reciclable (PRE) com a sortida d'energia del sistema de cultiu a l'indicador d'eficiència d'ús de la energia (PRE-EUE) (Navarro-Miró et al. 2019). El PRE inclou tota l'energia que potencialment es podria reciclar dins d'un sistema de cultiu, inclosa l'energia continguda en els ASC, la flora arvense i els residus del cultiu comercial (inclosos el descartat i altres residus). El PRE-EUE proporciona una visió de la capacitat del sistema de cultiu per transformar els inputs d'energia en energia potencialment reciclable. A la secció anterior ("Material i mètodes del capítol 2", pàgina 47) es mostra una descripció de les operacions agronòmiques realitzades en els experiments avaluats i dels equivalents energètics de les entrades i sortides utilitzades. A l'apèndix 2 (pàgines 206-216) d'aquesta tesi s'especifiquen els detalls dels procediments que s'utilitzen per atrapar els caràbids i estafilínids, així com el nombre i la durada dels períodes de mostreig, la determinació de l'activitat de l'enzim beta-glucosidasa i la valoració del nitrogen mineral del sòl després de la collita del cultiu comercial.

4.2.2. Indicadors agronòmics

Es va avaluar l'efecte de la gestió de l'ASC sobre els indicadors de rendiment i de qualitat del cultiu comercial. L'indicador de rendiment dels cultius es va avaluar mitjançant la biomassa seca del rendiment comercialitzable de la collita del cultiu, mentre que l'indicador de qualitat de la collita va incloure diferents mesures dels paràmetres de comercialització del cultiu, recollits a l'apèndix 2 (pàgines 206-216).

L’eficiència energètica de la producció comercialitzable va ser determinada per l’indicador d’eficiència d’ús energètic (M-EUE) (Barut et al. 2011), que quantifica l’eficiència d’un sistema de cultiu en la transformació d’entrades en sortides (Özgöz et al. 2017). Per a M-EUE, s’ha considerat exclusivament el rendiment comercial del cultiu com la sortida d’energia del sistema. La secció “3.2 Càlcul de les entrades i sortides d'energia” (pàgina 47) recull de manera detallada les operacions agronòmiques i els càlculs dels equivalents . El control de flora arvense es va analitzar mitjançant la determinació de la densitat de la flora arvense (individus m^{-2}). Per tenir en compte tots els efectes potencials de la competència amb els cultius comercials, es va incloure el nombre de plantes arvenses, provinents de la germinació de les llavors i els rebrots de plantes establertes, i el nombre de plantes de l’ASC durant la fase inicial del cultiu comercial, abans de la primera operació de desherbat. Els detalls específics del mostreig de la flora arvense es poden trobar a la secció anterior "2. Material i mètodes del capítol 1 ” (pàgina 41).

4.3 Anàlisis estadístiques

De la mateixa manera que a les seccions anteriors, en lloc d’analitzar les dades de diferents experiments de forma conjunta, es va establir un model estadístic per a cada experiment i indicador. Per als models lineals d'efectes mixtes, es va utilitzar la funció `lme` del paquet R `nlme` (Pinheiro et al. 2017), excepte en l’anàlisi de la lixiviació de nitrogen a BE-CRA-W i IT i de l’activitat del enzim beta-glucosidasa a IT, en què es va utilitzar la funció `lmer` del paquet R `lme4` (Bates et al. 2015). A IT, es va analitzar la densitat d’activitat dels caràbids, estafilínids i les aranyes mitjançant la funció `glmer.nb` del paquet `lme4` (Bates et al., 2015). A ES s’ha utilitzat models amb estructures de correlació espacial mitjançant la funció `gls`. Posteriorment, es va emprar un enfocament meta-analític per combinar els *P*-valors i analitzar l'efecte de la gestió de l’ASC per a cada indicador a través dels assajos. La secció “2.3 Anàlisis estadístiques” (pàgina 42) de l’apartat “2. Material i mètodes del capítol 1” recull una descripció més detallada del mètode analític.

Capitol 1. Els cultius amb serveis agroecològics gestionats amb el roller crimper redueixen la densitat i la riquesa d'espècies de la flora arvense en sistemes hortícoles ecològics a Europa

Títol: Agroecological service crops managed with roller crimper reduce weed density and weed species richness in organic vegetable systems across Europe

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Resum

Els cultius amb serveis agroecològics s’introdueixen en la rotació de cultius hortícoles per proporcionar serveis de regulació i suport i constitueixen una estratègia clau per a la gestió de la flora arvense en sistemes ecològics. Les agricultores i agricultors ecològics de tot Europa solen acabar aquests cultius abans del cultiu comercial mitjançant la seva incorporació al sòl amb la llaurada, utilitzant-los com adobs verds. Recentment, l’ús del roller crimper ha atret l’interès a tot Europa, ja que permet la deposició dels cultius amb serveis agroecològics sobre la superfície del sòl i crear solcs d'uns pocs centímetres d'amplada que faciliten la fertilització i el trasplantament d’hortalisses en cultius ecològics.

A Europa, la majoria de les investigacions sobre aquesta tecnologia s’han realitzat a Itàlia i no hi ha estudis que analitzin el seu efecte sobre la densitat i la riquesa d’espècies arvenses, i la composició de la comunitat arvense en diferents cultius, sòls i condicions climàtiques d’Europa. En aquest estudi, es compara els efectes de la deposició dels cultius amb serveis agroecològics amb el roller crimper respecte de la incorporació al sòl mitjançant la llaurada sobre l’abundància i la riquesa d’espècies arvenses, i la composició de la comunitat arvense en catorze experiments de cinc països al llarg de dos anys. El treball analitza l’efecte del roller crimper en els diversos experiments mitjançant un enfocament meta-analític basat en una versió ponderada del mètode de Stouffer.

Els resultats indiquen que la densitat mitjana de la flora arvense és el 35,1% menor a les parcel·les amb els cultius amb serveis agroecològics dipositats a la superfície del sòl

mitjançant el roller crimper que a les parcel·les incorporats al sòl mitjançant la llaurada, i aquesta tendència és significativa en els diversos experiments. A més, en aquest estudi es documenta la reducció significativa de la riquesa d'espècies arvenses amb aquesta tècnica i canvis significatius, però, de manera general menors, en la composició de la comunitat arvense en els diversos experiments. Per tant, aquest estudi posa de manifest per primera vegada l'eficàcia d'aquesta tècnica de gestió sobre el control de l'abundància de la flora arvense en les primeres etapes del creixement dels cultius hortícoles en un ampli ventall de cultius i condicions ambientals d'Europa. Tot i això, és important tenir en compte que l'efecte d'aquesta tecnologia es pot veure fortament afectat per les variacions de les condicions de cultiu.

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RESEARCH ARTICLE

Agroecological service crops managed with roller crimper reduce weed density and weed species richness in organic vegetable systems across Europe

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Abstract

Agroecological service crops are introduced into the vegetable crop rotation to provide agroecosystem services, and are a key strategy for weed management in organic systems. Organic farmers across Europe usually terminate these crops before cultivation of the subsequent cash crop, using them as green manure. Recently, the in-line tillage-roller crimper has attracted interest across Europe. It allows flattening the agroecological service crops and creates a narrow furrow that facilitates the fertilization and transplantation of organic vegetables. In Europe, most of the research on this technology has been carried out in Italy, and no studies are available analyzing its effect on weed density, weed species richness, and community composition in different vegetable crops, soils, and climatic conditions across Europe. We compared the effects of the usage of in-line tillage-roller crimper versus green manure on the weed abundance, species richness, and community composition in fourteen original datasets from five countries over 2 years. The support for a common effect of in-line tillage-roller crimper across trials was tested by means of a meta-analytic approach based on a weighted version of Stouffer's method. Our results indicate that in-line tillage-roller crimper management reduced weed density by 35.1% on average in comparison with green manure, and this trend was significant across trials. Moreover, we document a significant reduction of weed species richness under this technique and significant but, in general, minor changes in the weed community composition across the trials. Therefore, this study provides for the first time a solid evidence of the effectiveness of this management technique to reduce weed density at the early stages of crop growth across a wide range of vegetable systems and production conditions in Europe. Nonetheless, it is important to note that the effect of this technology can be strongly affected by variations in cropping conditions.

Keywords Agroecological service crops · In-line tillage · Mulch · Community composition

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1 Introduction

Agroecological service crops (ASCs) are sown in cropping systems to provide or promote agroecosystem services, independent of their position in the crop rotation and the method used to terminate them. This term includes catch crops, cover crops, and complementary crops (Canali et al. 2015). In vegetable systems, ASCs are usually grown during the cold rainy season. However, some authors have also highlighted the potential applicability of summer ASCs in southern Mediterranean regions of Europe, although their implementation is still limited (Canali et al. 2015).

In organic systems, ASCs are considered a key strategy for managing weeds (Gallandt 2014). To this end, numerous organic producers terminate the ASCs before the subsequent cash crop to avoid competition and reduce weed emergence. Nevertheless, some authors have noted that weed control effectiveness strongly depends on the termination technique selected (Canali et al. 2013; Ciaccia et al. 2016). Among European organic farmers, the most widespread management technique consists of chopping the ASCs and incorporating them into the soil by noninversion tillage (but sometimes plowing) as green manure (GM), while no-till methods are hardly used (Peigné et al. 2016). Despite the benefits of no-till practices for improving the quality of the soil (Sapkota et al. 2012), their adoption in organic systems is still limited because of important constraints mainly related to weed control (Casagrande et al. 2016).

However, in recent years, the no-till roller crimper (RC) for ASC management has attracted the interest of organic farmers and researchers across Europe (Casagrande et al. 2016; Vincent-Caboud et al. 2017). The RC allows flattening of the ASCs and creates a dense layer of plant residues (i.e., mulch) connected to the soil by the roots. The presence of mulch has physical and chemical effects, which can limit weed germination and seedling emergence. It has been shown that the extracts of some ASC species residues inhibit weed germination both in bioassays and open-field conditions (Ciaccia et al. 2015). The physical effect of the mulch might reduce weed density both by modifying the environmental conditions of the soil surface and by acting as a physical barrier that obstructs the development of the seedlings (Altieri et al. 2011). The flattened ASC modifies the soil temperature, surface daily temperature range, and soil water content (Altieri et al. 2011; Canali et al. 2013), which affects weed potential germination (Guillemin et al. 2013). Additionally, it reduces the light intensity that arrives at the soil surface (Teasdale and Mohler 2000), affecting the dormancy release and germination of many weed species (Batlla and Benech-Arnold 2014). Weed germination and emergence is also strongly conditioned by the mulch biomass and the specific weather conditions (i.e., temperature, rainfall) of the year. In general, the quantity of residues is more important than the type of residues, and the increase of the mulch biomass present on the soil surface decreases weed emergence exponentially (Teasdale and Mohler 2000). The specific weather conditions of the year can have an influence on both the ASC biomass production and the potential subsequent weed germination and emergence during the cash crop production (Carr et al. 2012; Canali et al. 2013).

Opposite results have been observed for the effect of mulch on weed species richness (Campiglia et al. 2010; Radicetti et al. 2013). Similarly, it is unclear how physical and allelopathic effects of mulch determine which species can germinate and emerge (Moonen and Bàrberi 2004). Mirsky et al. (2012) suggested that weed control by the mulch is species-specific and depends on both the sufficient quantity of mulch when a species is germinating and the energy reserves of propagules (i.e., big versus small seeds). Conversely, Campiglia et al. (2010) affirmed that the mulch acts to a greater extent on the number of individual plants irrespective of weed species. Furthermore, it is also important to note that some studies have reported shifts in the weed community composition in response to mulch presence (Campiglia et al. 2010; Radicetti et al. 2013).

The limited implementation and research on the no-till RC approach might be related to the predominant humid temperate climate of Europe (Mäder and Berner 2012). Additionally, in vegetable cropping systems, some agronomic difficulties, such as transplanting and fertilization of the vegetable crop, have hindered the adoption of this technique by organic famers (Luna et al. 2012; Canali et al. 2013). To overcome these limitations and facilitate the adaptation of this technology to organic European vegetable systems, the RC was modified by adding in-line tillage (in-line tillage/roller crimper, hereafter ILRC) (Canali et al. 2013). This modification, based on vertical sharpened discs and coulters arranged in line at the rear of the RC, allows flattening the ASC and simultaneously creating a narrow transplanting furrow without disturbing the surrounding mulch (Fig. 1).

Since its development, the research has mainly focused on analyzing the effect of cold rainy season ASCs managed with ILRC on weed abundance in zucchini and melon cash crops, and all these experiments have been carried out in the long-term MOVE trial located in Italy (Canali et al. 2013; Ciaccia et al. 2015, 2016). Moreover, most of the research focused on flattening the ASCs has been mainly focused on optimizing the RC design, selecting the best cold rainy season ASC composition, identifying changes in the abundance of perennial species, and analyzing the effect on cash crop development

Fig. 1 Pepper plant transplanted into a narrow furrow created by the ILRC after flattening the ASCs in Spain. Author: Alejandro Pérez-Ferrer

and production (Mirsky et al. 2012; Carr et al. 2012; Canali et al. 2013; Frasconi et al. 2019). However, to the best of our knowledge, only one study has focused on the effect of RC management on weed species richness (Halde et al. 2015), and another one has discussed, but not tested, its influence on weed community composition (Ciaccia et al. 2016). It therefore appears that the currently available information does not yet show robust evidence of the effectiveness of ILRC for weed control and the effect of this management technique on weed species richness and community composition across different vegetable crops, soils, and climatic conditions in European organic vegetable systems.

To fill this knowledge gap and investigate the potential for a wider adoption of this technology, this study aims to evaluate whether ASC management (GM vs. ILRC) affects the structural parameters of weed assemblages (weed density, species richness, and community composition). Moreover, we also evaluate the magnitude of the effects of ILRC compared with those of GM, and whether this effect is reliable or, on the contrary, depends on the variations in cropping conditions, and the ASC biomass produced. For these purposes, we analyzed fourteen original datasets on weed assemblages from five European countries over 2 years. The datasets are the result of a joint effort within the framework of the SoilVeg project, which aimed to analyze the applicability of ILRC to European vegetable agroecosystems. We hypothesized that (i) ILRC reduces weed density and species richness and modifies the community composition in comparison with GM ASC management, and (ii) the benefits of ILRC are strongly affected by variations in cropping conditions caused by interannual deviations in weather and in timing and effectiveness of field operations, as well as differences in relation to changing the area within the field. However, since we have not investigated these factors in detail, we consider that differences between years summarize these effects.

2 Materials and methods

2.1 Locations and trials

The organic vegetable field trials were located in Denmark (DK), Estonia (EE), Italy (IT), Slovenia (SI), and Spain (ES) for two consecutive years (Table 1). The locations were selected to cover a wide range of vegetable production conditions under different climatic zones of Europe (Metzger 2005). The trial established in DK represents the Atlantic North European climatic zone under the influence of the Atlantic Ocean, and it is characterized by cold winters and mild summers. The EE trial was located in the Nemoral zone, which is characterized by late spring and summer with high temperatures and abundant precipitation. The trial of SI represents the Alpine South zone characterized by the environmental conditions of the high mountains. The trials of ES and IT were located in the Mediterranean North zone, characterized by winters with maximum precipitation events and dry summers.

All partners (DK, EE, IT, SI, ES) grew the ASCs in the cold rainy season followed by a spring-summer cash crop. In parallel trials, in the Mediterranean countries (IT and ES), summer ASCs (warm-dry season) were also cultivated before the autumn-winter cash crop. Herein, IT-SCC and ES-SCC are used to refer to the main trials, and IT-ACC and ES-ACC are used for the parallel trials. Thus, in total, fourteen original datasets were analyzed (i.e., seven field experiments during two consecutive years) (Table 1).

2.2 Experimental design, management, and sampling methods of each trial

Cash crop management varied among partners depending on the climatic conditions, available machinery, and requirements of the selected vegetable crop. The experiment was repeated on the same plots in both years in ES. In all the other trials, the plots were moved to an adjacent area of the same experimental field. Each partner had a different experimental layout and management, but the comparison between ASCs' management was common to all (ILRC vs. GM). ILRC management consists of (i) several rapid passes of a roller crimper to flatten the ASCs, followed by (ii) a slower operation with an ILRC to create a narrow transplanting furrow without disturbing the surrounding mulch. GM management comprises (i) mowing-chopping the ASCs; (ii) incorporating ASCs into the soil by tillage, when the plant residues were dry; and (iii) seedbed preparation.

Each partner assessed weed and ASC species abundance at an early stage of the cash crop. Both germinated and resprouting individuals were counted and identified at the species level prior to weeding operations. These data provided measures of weed density and weed species richness. Weed density (individuals m^{-2}) comprised the total number of

Table 1 Data on the environmental conditions, ASCs, range of total dry biomass, cash crop, and weed sampling details of the seven trials included in this study

Country	Cash crop period	Temperature rainfall (annual mean)	Soil type	ASC	Range of total dry biomass (t/ha ASC+weeds)	Weed proportion of the total biomass (%)	Cash crop	Weed sampling (samples per plot)	Timing of sampling (days after transplanting)	Explanatory variables in the models
Denmark	SCC	1Y: 9.3 °C; 614 mm	Sandy loam	ASC 1–100% VF; ASC 2–100% PS; ASC 3–100% VS	2.32–6.74	7.66 ± 1.14	White cabbage	Four samples of 0.25 m^2	1Y: 26 days 2Y: 22 days	ASC management; total biomass; year
		2Y: 9.1 °C; 673 mm		ASC 4–50% SC + 50% VF; ASC 5–50% SC + 50% PS; ASC 6–50% SC + 50% VS	0.12–9.32	28.98 ± 7.05				
Estonia	SCC	1Y: 6.0 °C; 825 mm	Clay loam	1Y: ASC 1–100% SC; ASC 2–100% LM	3.84–11.20	1.98 ± 0.51	White cabbage	Four samples of 0.25 m^2	1Y: 69 days 2Y: 37 days	ASC management; total biomass; year; fertilization
		2Y: 5.8 °C; 694 mm		2Y: ASC 1–100% SC; ASC 2–100% TR	2.28–11.54	1.07 ± 0.09				
Italy	SCC	1Y: 16.7 °C; 539 mm	Clay	ASC 1–20% HV + 80% VS; ASC 2–20% HV + 80% VF	2.73–12.41	1.29 ± 0.54	Tomato	Four samples of 0.0625 m^2	1Y: 47 days; 2Y: 57 days	ASC management; total biomass; year; fertilization
		2Y: 16.5 °C; 402 mm			1.85–8.74	0.96 ± 0.25				
	ACC	1Y: 16.6 °C; 470 mm		ASC 1–100% VU; ASC 2–70% VU + 30% PG	2.29–6.29	19.02 ± 2.43	Cauliflower	Four samples of 0.0625 m^2	1Y: 28 days 2Y: 30 days	ASC management; total biomass; year
		2Y: 16.7 °C; 539 mm		ASC 3–50% VU + 50% PG; ASC 4–40% VU + 30% PG + 30% RS	1.60–5.44	20.72 ± 3.16				
Slovenia	SCC	1Y: 10.9 °C; 1009 mm	Loam	ASC 1–100% HV; ASC 2–100% TI	4.80–11.20	22.54 ± 1.91	Cauliflower	Two samples of 0.25 m^2	1Y: 43 days; 2Y: 29 days	ASC management; total biomass; year; fertilization
		2Y: 11.1 °C; 961 mm			2.51–11.43	31.24 ± 1.96				
Spain	SCC	1Y: 16.5 °C; 406 mm	Loam	ASC 1–100% CM (81% AB + 19% HV); ASC 2–50% CM + 50% VS	7.16–12.13	0.21 ± 0.04	Green pepper	Eight samples of 0.1 m^2	1Y: 21 days; 2Y: 22 days	ASC management; total biomass; year
		2Y: 16.1 °C; 409 mm			5.04–18.55	0.33 ± 0.06				
	ACC	1Y: 16.1 °C; 344 mm		ASC 1–100% VU; ASC 2–50% VU + 50% SB	2.92–16.35	70.89 ± 3.4	Savoy cabbage	Eight samples of 0.1 m^2	1Y: 30 days; 2Y: 36 days	ASC management; total biomass; year
		2Y: 16.5 °C; 406 mm			0.98–19.23	63.95 ± 4.01				

SCC, spring-summer cash crop; *ACC*, autumn-winter cash crop; *1Y*, first year; *2Y*, second year of experimentation; *VF*, *Vicia faba* var. *equina* Pers.; *PS*, *Pisum sativum* L.; *VS*, *Vicia sativa* L.; *SC*, *Secale cereale* L.; *LM*, *Lolium multiflorum* Lam.; *HV*, *Hordeum vulgare* L.; *VU*, *Vigna unguiculata* (L.) Walp.; *PG*, *Pennisetum glaucum* (L.) R.Br.; *RS*, *Raphanus sativus* L.; *TI*, *Trifolium incarnatum* L.; *CM*, cereal mixture composed by 81% AB + 19% HV; *AB*, *Avena byzantina* K.Koch.; *SB*, *Sorghum bicolor* (L.) Moench; *TR*, ×*Triticosecale blaringhemii* A.Camus germinated and resprouting individuals, including weed and ASC species, to account for all the potential competition towards cash crops. On the other hand, weed species richness (number of species/sample) and community composition referred exclusively to weeds germinated at the beginning of the cash crop. In these cases, we analyzed exclusively germinated weeds to isolate the response of weed communities to the different ASC management methods. Weed species abundances were averaged for each plot in all trials, except in ES where the exact locations of samples were taken into account (see below). Weed species richness cannot be standardized to fixed surface and therefore, in each trial, weed species richness referred to the sampling frame.

Specific information on the environmental conditions (i.e., annual mean temperature and rainfall, soil texture), ASC composition, range of total dry biomass, cash crop grown, and weed sampling procedure of the seven trials included in this study is detailed in Table 1.

2.2.1 Denmark

The field experiment was conducted at the research center of the Department of Food Science of Aarhus University located in Årslev (Denmark) (10°27′ E; 55°18′ N). The trial was newly established and the previous crop grown in the area was barley (*Hordeum vulgare* L.). The trial was established on a sandy loamy soil with a 1% carbon in the 0–0.5-m soil layer. The trial had a split-plot randomized complete block experimental design with three replicates, where ASC management (i.e., ILRC vs. GM) was the whole-plot factor, while ASC composition was the subplot factor (i.e., six different ASC compositions) (Table 1). The plot size was 3.2 m × 10 m during the first year and 4.8 m × 10 m during the second year. White cabbage (*Brassica oleracea* var. *capitata* L.) was transplanted on July 1, 2016, and on June 21, 2017. The harvest was carried out on November 11, 2016, and on November 2, 2017. During the first year, all the plots were fertilized prior the ASC plantation (October 5, 2015) with feather meal pellets (26 kg N ha^{-1}) and during the cabbage development (50 kg N ha^{-1}) (August 25, 2016). Cash crop was irrigated two times, on August and September, with sprinklers. During the second year, plots were fertilized with feather meal (26 kg N ha^{-1}) prior to the ASC plantation (October 9, 2016), a week before the cabbage transplantation with feather meal pellets (100 kg N ha^{-1}) and lupine seeds (30 kg N ha^{-1}), and during the cabbage development with feather meal pellets (80 kg N ha^{-1}) (August 24, 2017). In this cash crop cycle, no irrigation was required. Weeds were evaluated in 0.5 m × 0.5 m quadrats randomly distributed on each plot, and one cabbage plant was included in each quadrat. In 2016, weeds were sampled 26 days after transplanting, while in 2017, the sampling was carried out 22 days after transplanting.

2.2.2 Estonia

The field experiment was conducted at the experimental organic research field in eastern Estonia at Jõgeva (Estonia) (58°44′ N; 26°24′ E). The trial was newly established on a certified organic area since 2005. Previously, the area was used for organic arable crop experimentation. Specifically, the previous crop grown was red clover (*Trifolium pratense* L.). The experimental field was located on a clay loamy soil with a 3% organic carbon. The experimental design was a strip-plot design with ASC strips and ASC management crossed with the fertilizing factor (i.e., manure vs. without manure), and three replicates per treatment. The plot size was 6 m × 4 m. White cabbage was transplanted in the first year from the 13th to the 16th of June 2016, and in the second year on June 19, 2017. The harvest was carried out on October 7, 2016, and from October 4 to 6 in 2017. Plots belonging to the fertilization treatment were fertilized before the ASC plantation with the application of 30 t/ha solid cattle manure (153 kg ha^{-1} N, 57 kg ha^{-1} P, and 81 kg ha^{-1} K). During the second year, all plots were fertilized 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 year, cash crop was not irrigated. Conversely, during the second year, all plants were watered one time in mid-July with a humic solution (0.0003 kg ha^{-1} N, 0.0001 kg ha^{-1} P, 0.0002 kg ha^{-1} K). Weeds were evaluated in 0.5 m × 0.5 m quadrats in each plot, placed at 0.5 m from plot borders. During the first year, weeds were sampled 69 days after transplanting, while in the second year, the sampling was carried out 37 days after transplanting.

2.2.3 Italy

The field experiment was conducted in the Experimental Farm of Metaponto belonging to the Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria in Southern Italy (40°24′ N; 16°48′ E). Both parallel field experiments (i.e., spring-summer cash crop (SCC) and autumn-winter cash crop (ACC)) were newly established. The previous crop grown was wheat (*Triticum aestivum* L.) in the ACC trial and fennel (*Foeniculum vulgare* Mill.) in the SCC trial. Soil texture was clay loam and contained on average 1.1% of organic carbon. In both trials, the plot size was 6 m × 4 m. Weed samplings were carried out in four 0.25 m × 0.25 m quadrats randomly distributed in each plot in both trials.

Spring-summer cash crop The experimental design was a split-split-plot with main plots arranged as a randomized complete block design, with three factors and three replications. The main plot was assigned to the ASC factor (i.e., two ASC compositions), the subplot to the ASC management (GM vs. ILRC), and the split-plot to the fertilization factor (three levels). The fertilization factor consisted in (i) no fertilizer,

(ii) commercial organic mineral fertilizer allowed in organic farming, and (iii) anaerobic digestate from cattle residues. The tomato (*Solanum lycopersicum* L.) was transplanted on April 28, 2016, and on May 5, 2017, and harvested from July 7 to August 25 in 2016, and from July 18 to August 25 in 2017. Crop was drip-irrigated weekly. Weed sampling was carried out 47 days after transplanting in the first year, and 57 days after the cash crop transplanting in the second year.

Autumn-winter cash crop The experimental layout was a split-plot with main plots arranged as a randomized complete block design, with two factors and three replications. The main plot was assigned to the ASC composition (four levels) (Table 1) and the subplot was assigned to the ASC management factor levels with two levels (GM vs. ILRC). The ASC was grown in the warm/dry season, followed by cauliflower (*Brassica oleracea* var. *botrytis* L.) as cash crop, which was transplanted on August 3 of both years. The cauliflower harvest was from November 23 to December 15 in 2015, and on November 28, 2016. No fertilization was applied before the ASC sowing. Off-farm animal manure–based organic fertilizer was applied just before the ASC termination, while the second was applied localized on the cauliflower plants during the cash crop plant development. The total fertilizer rate was 150 kg ha^{-1} N, 450 kg ha^{-1} P_2O_5, and 150 kg ha^{-1} K_2O. ASC and cauliflower crops were irrigated on both years of experimentation by micro-sprinklers. ASC was irrigated on the emergence, while cauliflower was watered according to crop requirements each year. Weed sampling was performed in the first year 28 days after transplanting, while in the second year 30 days after transplanting.

2.2.4 Slovenia

The field experiment was conducted at the University of Maribor (Pivola), Faculty of Agriculture and Life Sciences (UM), Slovenia (46°30′ N; 15°37′ E). The trial was newly established in a field in which barley was produced the year before. The soil was characterized by a loam texture with an average of 2.66% of organic carbon in the 0–0.30-m soil layer. The experimental design was a split-split-plot with plots arranged as a randomized complete block design, with three factors (i.e., ASC composition, ASC management, and fertilization) and four repetitions. ASC composition had two levels (Table 1), ASC management had two levels (GM vs. ILRC), and the fertilization factor had two levels (i.e., application of 30 t ha^{-1} of livestock manure before sowing ASC vs. without manure application). The plot size was 2.5 m × 2.5 m. Cauliflower was transplanted in the first year on June 3, 2016, and on May 24, 2017, and harvested on September 29, 2016, and September 5, 2017. During both years of experimentation, all plots were fertilized two times during the cash crop cycle using organic amendments. The first application was carried out at the cash crop transplanting (70 kg ha^{-1} N), while the second fertilization (70 kg ha^{-1} N) was performed during the development of the cash crop. Irrigation was required in the second year of experimentation two times during the cash crop development. Weeds were sampled in four 0.5 m × 0.5 m quadrats randomly placed in each plot. In the first year, weeds were sampled 43 days after transplanting, while in the second year, 29 days after transplanting.

2.2.5 Spain

Spring-summer cash crop and autumn-winter cash crop Field experiments were conducted at the Gallecs Area of Natural Interest (Barcelona, Spain) (41°33′ N; 2°12′ E). The trial was newly established in an area which began the conversion to organic farming in 2005. The previous crop grown in the area was wheat. The trials were characterized by loamy soil texture and the mean proportion of organic carbon is 0.95%. In both parallel trials (i.e., SCC and ACC), the experimental design was a randomized strip-plot with two factors (the ASC composition and ASC management) (Table 1) and four replicates. The different treatments were established in parallel bands randomly distributed, and four plots of 6 m × 4 m were defined within each band. The experimental design was conditioned largely by the need to perform all agricultural works in the same direction and facilitate machinery traffic between plots. In the SCC trial, green pepper (*Capsicum annuum* L.) was transplanted on May 26, 2016, and on June 20, 2017. The last pepper harvest was on October 3, 2016, and on October 2, 2017. In ACC, savoy cabbage (*Brassica oleracea* var. *sabauda* L.) was transplanted on August 4, 2015, and on September 20, 2016. The last savoy cabbage harvest was carried out on December 2, 2015, and on February 22, 2017. In SCC, fertilization was carried out just after transplanting using a commercial organic fertilizer (i.e., 170 kg ha^{-1} N). In ACC, in both years, the fertilizer amount was the same (100 kg ha^{-1} N); however, in the first year, the fertilization was split in two applications (i.e., one just after transplanting and the other during the development of the cabbage), while in the second year, only one fertilization was carried out just after transplanting. In ACC, ASC was irrigated sprinklers in both years, while cabbage was watered according to the crop needs by using drip irrigation. In SCC, only the cash crop was drip-irrigated according to the crop needs. In both trials, eight samples of 0.25 m × 0.40 m were taken per plot. The samples were placed so that the corner of each sample leaned on a cash crop plant, and the longest side was placed perpendicular to the cash crop line.

2.3 Statistical analysis

We did not pool the raw data from different experiments because each trial had its own experimental design; instead, a specific statistical model was used for each trial. Then, we used a meta-analytic approach to test for the overall statistical support for the effect of ASC management on weed density and weed species richness.

Each statistical model included all the experimental variables evaluated in each specific trial (Table 1) to discount their effect in the dependent variable. Only termination (GM and ILRC), year (year 1 and year 2), and total dry biomass were explanatory variables common to all experiments. The first two were included as factors, whereas biomass was included as a covariate. Given the specifics of each trial, the year summarizes the variations in the cropping conditions caused by interannual variations in weather and timing and effectiveness of field operations, as well as differences in relation to changing the area within the field. We pooled the total dry biomass of the different ASCs included in each trial and the weeds present prior to the ASC termination. In the trials which included fertilization, the levels of this factor were defined specifically according to the description in Section 2.1.

In DK, EE, IT, and SI, linear mixed-effects models were used for each partner and year. The specific experimental layout of each trial, described in the previous section, defined the selection of the random effects for these trials.

In ES, the need to facilitate the machinery traffic between plots conditioned the experimental design. Thus, spatial correlation structures were introduced in ES models to account for the lack of independence between samples (Pinheiro et al. 2000). Models including the different classes of spatial correlation structures as well as a model without a spatial correlation structure were compared by likelihood ratio tests and by Akaike's information criterion (AIC) to establish the best model for each dependent variable and year.

When needed, data were transformed to meet the requirements of normality and homoscedasticity. Weed density was transfomed applying logarithms (IT-SCC-pooled; ES-ACC-pooled) and square root transformation (SI-SCC-pooled; ES-SCC-pooled). Weed species richness was transformed applying logarithms (EE-SCC-1Y; EE-SCC-2Y). All statistical analyses were performed with R software (R Core Team 2017); for linear mixed-effect models, we used the lme function of the R nlme package (Pinheiro et al. 2017), while for ES models with spatial correlation structures, we used the gls function.

The meta-analytic approach was applied to analyze the effect across trials of the ASC management on weed density and weed species richness. This meta-analytic approach can be nearly as powerful as that based on combining data (Zaykin 2011). We used the weighted Z test, which is essentially a weighted version of Stouffer's method:

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

where $Z_i = \Phi^{-1}(1 - p_i)$; p_i is the p value from the ith study out of k studies in total; w_i is the weight selected for the study; and Φ and Φ^{-1} are the standard normal cumulative distribution function and its inverse, respectively. For this study, we weighted the Z_i by the standardized effect size, as suggested by Zaykin (2011):

$$w_i = \frac{|\mu_i|}{SE_i}$$

where μ_i is the coefficient estimate and SE_i is its standard error. For testing the same alternative hypothesis, individual p values were converted to one-sided before combining as follows (Zaykin 2011):

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

Independence among p values is required for the weighted Z test. Thus, we pooled the data from the two consecutive years in each trial to analyze the effect of the termination in each trial.

Community composition shifts were analyzed using permutational multivariate analysis of variance (PERMANOVA). Prior to PERMANOVA, we carried out the steps suggested by Anderson (2001): (i) we transformed the weed abundance measurements into presence/absence data; (ii) we used the Jaccard distance to compute the distances between plots; and (iii) we tested for homogeneity in multivariate dispersion with the betadisper function of the R package vegan (Oksanen et al. 2017). PERMANOVA was performed with the adonis function with the R package vegan (Oksanen et al. 2017). Specifically, it decomposes the variance of the distance matrices and attributes the components of the variance (i.e., measured as partial R^2) to the explanatory variables (i.e., factors and covariates).

The relative importance of the effect size of total dry biomass (ASCs + weeds), year, and termination was also calculated. For weed density and species richness, the estimated coefficient for each explanatory variable was divided by the intercept of the model (Armengot et al. 2015), while for the community composition, the effect size was related to the partial R^2 of each variable for each trail (Koricheva et al. 2013).

3 Results and discussion

3.1 Effect of ILRC management on weed density, species richness, and community composition

The ASC management had a clear effect on weed density, species richness, and community composition at the beginning of the cash crop (Table 2). ILRC management dramatically reduced weed density, and this effect was robust among trials. The mean across experiments showed that ILRC management reduced weed density by 35.1% in comparison with GM. In addition, analyzing both years pooled, the results of the meta-analysis showed that this trend was significant across trials (Fig. 2a). Specifically, ILRC reduced weed density at least in one of the two years in five (DK, EE, ES-SCC, ES-ACC, SI) out of the seven trials, and in two of them (DK, SI), this trend was significant in both years of experimentation (Fig. 2a). Previous field experiments in Italy have also reported a dramatic reduction in weed abundance in ILRC plots, averaging 86% (Canali et al. 2013) and 83.5% (Ciaccia et al. 2016) in comparison with GM. The pattern observed in our study could be related to the presence of mulch, which modifies the light and the temperature at the soil surface (Teasdale and Mohler 2000; Canali et al. 2013), both crucial factors affecting dormancy and germination of many weed species (Guillemin et al. 2013; Batlla and Benech-Arnold 2014).

Weed species richness also had a consistent response to ILRC management during the first 2 years of experimentation across trials (Table 2). ILRC management reduced species richness by 23.8% across trials, and this trend was significant according to the weighted Stouffer test (Fig. 2b). ILRC termination reduced weed species richness in at least one of the years of experimentation in all the countries except Italy, and in three of them (DK, EE, ES-ACC), this trend was significant in both years of experimentation (Fig. 2b). The immediate response observed after the adoption of ILRC management across trials diverged with the only study available so far (Halde et al. 2015), in which a significant response was observed in the fifth year of continuous management in arable rainfed crops. Furthermore, the consistent weed species richness reduction across trials observed in our study contrasts with previous studies. Positive and negative effects have been observed for the effects of tillage intensity (Nichols et al. 2015; Armengot et al. 2015) and the presence of mulch (Campiglia et al. 2010; Radicetti et al. 2013) on weed species richness.

The general pattern observed for weed density and species richness under ILRC across trials contrasts with the local results of the trials carried out in Italy (i.e., ACC and SCC). In these trials, weed density and species richness were not reduced under ILRC management, and even a significant increase of weed density was noticed in the first and second year of experimentation of IT-ACC (Fig. 2a, b). The atypical pattern observed for weed density in IT-ACC trial could be related to the ASC and weed resprouting, while the absence of effect on weed species richness might be a consequence of the low levels of weed density in the experimental field where the trials were carried out (Table 2).

Analyzing weed species from the fourteen datasets, we observed that overall weed communities after the ASC management were dominated by annual and broadleaf species (Table 2). Weed community composition generally had a significant but low response to ASC management (ILRC vs. GM) in most of the trials analyzed. Specifically, in all the trials except in the Italian ACC, the composition of weed communities was significantly affected by the ASC management in both years of experimentation (Fig. 2c). Nonetheless, the percentage of weed community composition variability attributable to termination was generally low and ranged from a minimum value of 8.2% in the second year of the Italian SCC trial ($p = 0.005$) to a maximum of 34.3% in the second year of the trial in Slovenia ($p = 0.001$) (Fig. 2c). On the other hand, the average Jaccard distances between ASC managements (Table 2) indicate that the differences between ILRC plots are similar or even higher than between ILRC and GM plots. In all trials except the Italian ones, the ILRC plots were significantly more variable in weed composition than the GM ones. ILRC reduced drastically weed density and species richness, and this effect was rather unspecific, causing a strong divergence between samples, which means that ILRC does not select some species over others. Previous studies have reported changes in weed community composition produced by both tillage intensity changes (Nichols et al. 2015; Armengot et al. 2015) and mulch presence (Campiglia et al. 2010; Radicetti et al. 2013). However, as far as we know, only one study has considered the effect of ILRC management on weed community composition (Ciaccia et al. 2016). In this study, the authors speculate that ILRC could influence the weed community composition in organic vegetable cropping systems, but they did not statistically compare the differences between ILRC- and GM-managed plots.

In this study, weed density, species richness, and community composition were analyzed only at the early stages of crop growth. Nonetheless, some weed species might emerge later in the crop cycle due to the modifications of the soil

Table 2 Weed density (individuals m^{-2}), weed species richness (species sampling $unit^{-1}$), weed community composition (EPPO codes), and average Jaccard distances between terminations per year, trial, and ASC management. Weed density and weed species richness are also summarized pooling both years' data

	DK - SCC		EE - SCC		ES - SCC		ES - ACC		IT - SCC		IT - ACC		SI - SCC	
	GM	ILRC	GM	ILRC	GM	ILRC	GM	ILRC	GM	ILRC	GM	ILRC	GM	ILRC
Density														
Year 1	502 ± 32	181 ± 20	159 ± 10	39 ± 3	471 ± 56	257 ± 40	252 ± 11	61 ± 4	52 ± 7	66 ± 11	84 ± 13	114 ± 9	181 ± 16	33 ± 3
Year 2	1057 ± 61	406 ± 35	190 ± 19	66 ± 5	297 ± 20	137 ± 15	1055 ± 43	1032 ± 111	21 ± 3	20 ± 2	130 ± 13	184 ± 24	718 ± 25	250 ± 14
Pooled	780 ± 58	293 ± 27	175 ± 11	57 ± 5	384 ± 31	197 ± 23	653 ± 55	546 ± 82	36 ± 5	43 ± 7	107 ± 10	149 ± 14	449 ± 50	141 ± 21
Species richness														
Year 1	8.2 ± 0.2	5.4 ± 0.3	8.6 ± 0.3	5.2 ± 0.2	5.3 ± 0.2	4.3 ± 0.5	6 ± 0.2	0.7 ± 0.1	1.3 ± 0.1	1.1 ± 0.1	1.2 ± 0.1	1.2 ± 0.1	5.5 ± 0.2	3.2 ± 0.2
Year 2	10.9 ± 0.2	8.7 ± 0.2	11.2 ± 0.6	8.3 ± 0.5	4.9 ± 0.2	3.2 ± 0.2	8.3 ± 0.2	5.7 ± 0.3	1 ± 0.1	1.1 ± 0.1	2.1 ± 0.2	2.4 ± 0.2	6.6 ± 0.2	6.1 ± 0.2
Pooled	9.5 ± 0.3	7.1 ± 0.3	9.9 ± 0.4	7.3 ± 0.5	5.1 ± 0.1	3.8 ± 0.3	7.1 ± 0.2	3.2 ± 0.4	1.1 ± 0.1	1.1 ± 0.1	1.6 ± 0.2	1.8 ± 0.2	6 ± 0.2	4.6 ± 0.3
Community composition														
Year 1														
First more abundant	STEME	VERAR	ARTVU	MATIN	POROL	SOLNI	AMARE	VERPE	CONAR	CONAR	POROL	POROL	GASPA	CAPBP
Second more abundant	VERAR	STEME	ERYCH	LAMPU	SOLNI	POROL	SOLNI	STEME	ECAEL	ECAEL	EPHPT	CONAR	POROL	ECHCG*
Third more abundant	CHEAL	CAPBP	CAPBP	SONAR	AMARE	AMARE	DIPER	SETVE*	SONOL	PHAMI	CONAR	SONAR	AMARE	STEME*
Fourth more abundant	LAMPU	SENVU	LAMPU	MYOAR	HEOEU	SETVE	POROL	AMARE*	SONAR	PHAPA	SONAR	ECHCG	ECHCG	GASPA
Fifth more abundant	CAPBP	LAMPU	CHEAL	AGRRE	AMABL	DIPER	VERPE	CYPRO	POROL	SONOL	ECHCG	EPHPT	POLHY	AMARE
Year 2														
First more abundant	POAAN	VERAR	CHEAL	STEME	AMARE	POROL	STEME	STEME	CONAR	CONAR	CONAR	CONAR	ECHCG	STEME
Second more abundant	POLPE	POAAN	STEME	VIOAR	POROL	AMARE	VERPE	VERPE	ECAEL	ECAEL	SONOL	ECAEL	AMARE	LAMAL
Third more abundant	STEME	STEME	LAMPU	POATR	SOLNI	HEOEU	DIPER	CLDAR	POROL	PICEC*	ECAEL	SONOL	GASPA	AMARE*
Fourth more abundant	LAMPU	LAMPU	VIOAR	MYOAR	HEOEU	SOLNI	POROL	SETVE	EPHPT	BEAVX*	POROL	BEAVX	LAMAL	ECHCG*
Fifth more abundant	VERAR	POLPE	ERYCH	LAMPU	DIPER	CHEAL	SETVE	AMARE	ECHCG	CHEAL*	BEAVX	AMARE	POLHY	GASPA
Jaccard distance														
GM	0.22		0.40		0.54		0.59		0.65		0.50		0.26	
ILRC	0.33	0.37	0.52	0.50	0.53	0.54	0.59	0.60	0.71	0.68	0.50	0.48	0.55	0.54

DK, Denmark; *EE*, Estonia; *IT*, Italy; *SI*, Slovenia; *ES*, Spain; *SCC*, spring-summer cash crop; *ACC*, autumn-winter cash crop; *ILRC*, in-line tillage/roller crimper; *GM*, green manure. EPPO codes followed by an asterisk indicate species that are equally abundant. EPPO codes correspondence can be found in the EPPO Global Database webpage: https://gd.eppo.int/

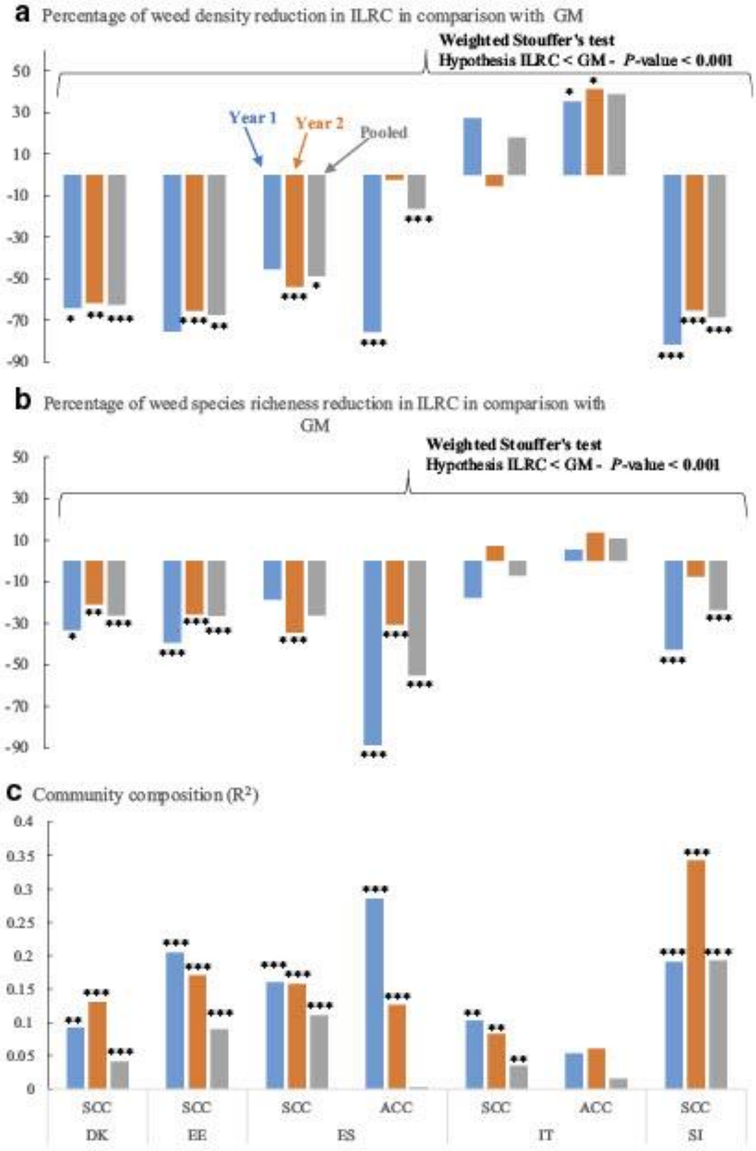

Fig. 2 **a** Percentage of weed density reduction in ILRC in comparison with GM. **b** Percentage of weed species richness reduction in RC in comparison with GM. **c** Community composition (R^2). DK: Denmark, EE: Estonia, IT: Italy, SI: Slovenia, and ES: Spain. SCC: spring-summer cash crop; ACC: autumn-winter cash crop; ILRC: in-line tillage/roller crimper; GM: green manure. Significance codes: *$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$

surface environment (Guillemin et al. 2013). These weeds could also compete for water and nutrients, and also cause problems during the harvest of some vegetables. Thus, this evaluation should be completed with studies analyzing the weed emergence and growth during the development. Additionally, ILRC long-term studies in vegetable systems are required to provide information on the cumulative effect of this technology over the years. According to previous studies focused on arable crops (Halde et al. 2015), one of the expected cumulative effects is the progressive establishment and proliferation of perennial weed species, which hinder the management of the cropping system and might affect cash crop yield.

3.2 Effect size of the explanatory variables on structural parameters of weed communities

Despite important implications from an agronomic point of view, there are no direct comparisons analyzing the relative importance of the explanatory variables (dry biomass, year, ASC management) in vegetable cropping systems using ASC. To fill this knowledge gap, in our study, we analyzed the effect size of the explanatory variables on structural parameter of weed communities (weed density, species richness, and community composition). We have found that the relative importance of the explanatory variables varied depending on the structural parameter of weed communities and the trial analyzed (Fig. 3).

ASC biomass flattened or chopped and incorporated into the soil is usually considered an important factor for controlling weeds (Radicetti et al. 2013; Canali et al. 2013; Ciaccia et al. 2016). However, in our study, the comparison of the size effects of the explanatory variables on weed density across trials reflected that the relative importance of total dry biomass was low in all cases (Fig. 3) despite the wide ranges of this variable and the different weed proportions in the total dry biomass managed across trials, years, and partners (Table 1). ASC management (ILRC vs. GM) and the variations in the cropping conditions (i.e., year) are more important than the biomass produced by the ASCs for weed density (Fig. 3). Specifically, year had the largest effect size on weed density in four out of the seven trials evaluated. Thus, our results suggest that the reduction of weed density produced by ILRC management can be strongly affected by variations in cropping conditions. Previous studies have noticed a significant effect of both the year and ASC management on weed abundance under ILRC management, but the relative importance of each variable was neither analyzed nor discussed (Canali et al. 2013).

Some authors have suggested that community composition is mainly affected by the tillage intensity, while the weed species richness is a result of both the management and the environmental conditions (Nichols et al. 2015). Our results showed that both community composition and species

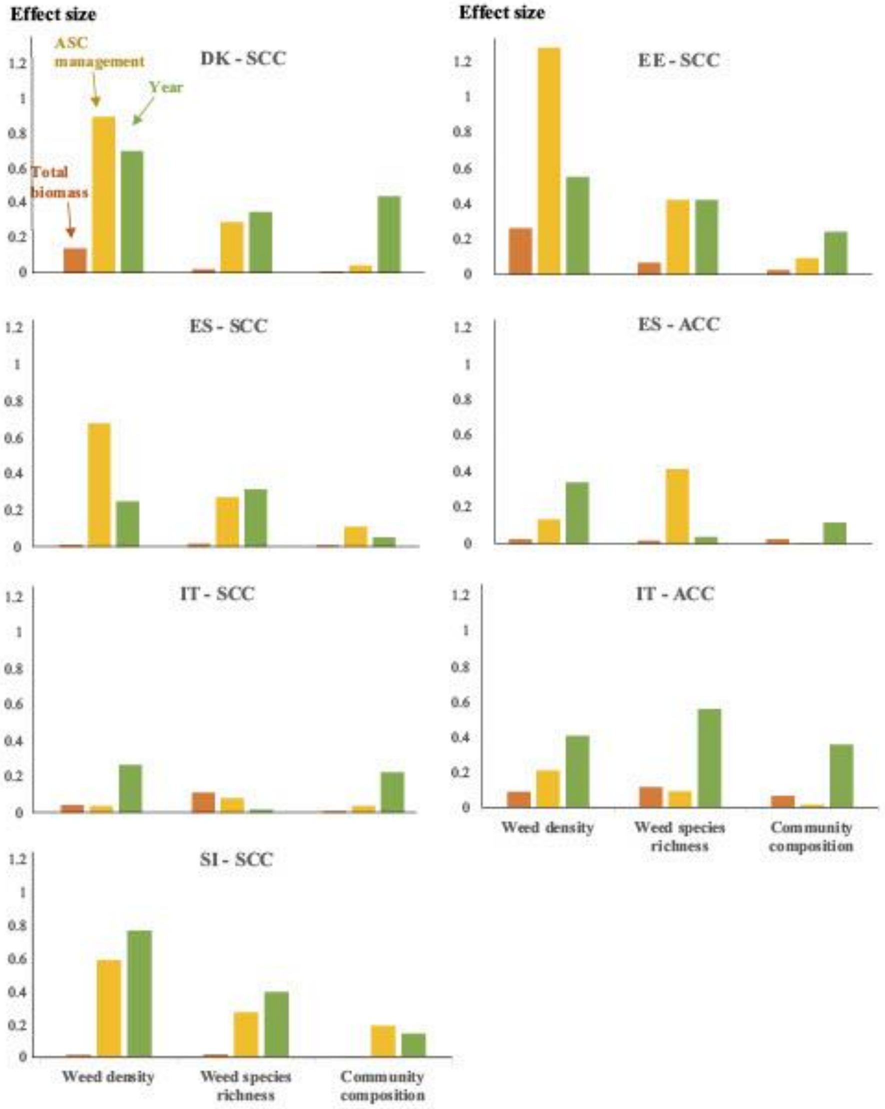

Fig. 3 Relative importance of the total dry biomass prior to ASC termination, the ASC management, and the year on the weed density, species richness, and community composition. For weed density and species richness, the estimate value of each variable was divided by the intercept of the model for each trial. In community composition, the R^2 was calculated for variable for each trial. DK: Denmark, EE: Estonia, IT: Italy, SI: Slovenia, and ES: Spain. SCC: spring-summer cash crop; ACC: autumn-winter cash crop; ILRC: in-line tillage/roller crimper; GM: green manure

richness were influenced by the year and ASC management, and their relative importance varied across trials (Fig. 3). Nonetheless, the year had a larger effect size in more trials than ASC management both for weed species richness and community composition. Total dry biomass presented the lowest relative importance in all trials, except in IT-SCC for weed species richness.

Therefore, our study indicates, for the first time, that the variations in the cropping conditions can strongly affect the outcome of ASC management on the structural parameters of weed communities (weed density, species richness, and community composition). Furthermore, we also note that the effect of the flattened or green manured total dry biomass is less important than the effect of both ASC management and cropping conditions on weed density, species richness, and community composition for most of the trials analyzed.

4 Conclusions

This study, which includes fourteen datasets from five different countries across Europe, provides for the first time solid evidence of the effectiveness of ILRC management for weed control at early stages of crop growth in different vegetable systems, soils, and climatic conditions across Europe. However, most importantly, although the benefits of ILRC management can be strongly affected by variations in cropping conditions (including but not restricted to interannual weather conditions, timing and effectiveness of field operations, variations between fields), our results provide a successful example that can contribute to reduce the reliance on tillage for weed management in organic vegetable systems.

Our multisite study also contributes to reduce the knowledge gap existing in the literature regarding the impact of ILRC management on weed species richness and community composition. We document for the first time a general trend under ILRC management of reduced weed species richness in seven trials across Europe in the transition to this management technique. Additionally, we report a significant but generally low effect of ASC management on weed community composition in most of the trials analyzed. Furthermore, we note that the effect of the total dry biomass, either flattened or used as green manure, is less important than the effect of both ASC management and the yearly conditions on weed density, species richness, and community composition for most of the trails analyzed.

Further research is required to identify the effect of the presence of mulch in ILRC systems on the environmental conditions of the soil surface, in different soils and climatic conditions across Europe, and how it affects the emergence of weeds along the cash crop cycle. Additionally, before this strategy can be suggested to farmers as a continuous management to be followed along the years, long-term studies analyzing the effect of this technology in the weed community composition would be required.

Authors' contributions David Navarro-Miró contributed to the design of the work, collected and analyzed the data, interpreted the results, and drafted the article. José M. Blanco-Moreno contributed to the analysis of data, the interpretation of the results, and the drafting of the article. Corrado Ciaccia contributed to the conception and design of the work and collected and analyzed data. Lourdes Chamorro, Hanne Lakkenborg Kristensen, Margita Hefner, Kalvi Tamm, Elena Testani, Ingrid Bender, Urška Lisec, Martina Bavec, Hélène Vedie, and Līga Lepse contributed to the design and management of the experiments and collection of data in each country. Stefano Canali (SoilVeg project coordinator) conceived the trans-national, multisite, and multi-season dimension of the entire experiment. F. Xavier Sans had a major role in the conception and design of the work, data analysis, and interpretation of the results and contributed to drafting the article. All the authors critically revised the final manuscript.

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Compliance with ethical standards

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Capítol 2. Els fluxos d’energia als sistemes hortícoles ecològics europeus: efectes de la introducció i la gestió de cultius de serveis agroecològics

Títol: Energy flows in European organic vegetable systems: effects of the introduction and management of agroecological service crops

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Resum

Reduir les aportacions externes mitjançant la promoció del reciclatge d’energia en els sistemes de cultiu és un dels principis de l’agricultura ecològica. En aquest context, la implementació i la gestió adequada dels cultius amb serveis agroecològics (ASC) pot tenir un paper clau. Pocs estudis han analitzat l'efecte de la introducció dels ASC i han comparat els fluxos d'energia en la gestió del ASC mitjançant la incorporació al sòl amb la llaurada (T-GM) i mitjançant la deposició a la superfície del sòl amb el roller crimper (NT-RC). A més, els estudis dels fluxos d’energia actuals no tenen en compte totes les fonts d’energia que es poden reciclar dins d’un sistema de cultiu i cap d’ells ha avaluat l’eficiència en el reciclatge d’energia dels sistemes de cultiu.

El nostre estudi, que va recopilar informació sobre vuit experiments situats a sis països europeus al llarg de dos anys, mostra que la inversió energètica mitjana és un 19,73 % major en els sistemes que incorporen l’ASC que els sistemes sense ASC. No obstant això, les estratègies de gestió que utilitzen l’ASC tendeixen a augmentar l'energia que potencialment es podria reciclar dins del sistema. A més, aquest estudi també proporciona, per primera vegada, proves de que el sistema de gestió NT-RC redueix l'eficiència productiva comercialitzable respecte a T-GM, però millora l’acompliment ambiental mitjançant l’augment de l'energia potencial que es pot reciclar dins del sistema de cultiu en una àmplia gamma de condicions pedo-climàtiques europees.

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Energy flows in European organic vegetable systems: Effects of the introduction and management of agroecological service crops

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ABSTRACT

Reducing inputs by promoting the recycling of energy within a cropping system is one of the principles of organic farming. To this end, the introduction and proper management of agroecological service crops (ASC) can play a key role. Few studies have analysed the effect of ASC introduction and compared energy flows under green manure (ASC-GM) and no-till roller crimper (ASC-NT) management. Moreover, current energy flows studies do not account for all the sources of energy that could be recycled within a cropping system, and none of them have evaluated the efficiency of cropping systems for recycling energy.

Our study, which gathered information on eight field experiments across six European countries over two years, indicates that ASC inclusion and management required, on average, a 19.73% higher input investment than systems that did not include them. Nevertheless, ASC management strategies were more prone to increase the energy that potentially could be recycled within the cropping system. Moreover, this study also provides, for the first time, evidence that ASC-NT reduces the marketable production efficiency relative to ASC-GM but improves the environmental performance by increasing the potential energy that can be recycled within the cropping system across a wide range of European pedo-climatic conditions.

1. Introduction

Organic agriculture aims to develop sustainable farming systems. To this end, the principle of ecology defined by the International Federation of Organic Agriculture [1] encourages input reduction by improving the management, reuse and recycling of energy and materials. In this context, the introduction of agroecological service crops (ASC) in crop rotation may reduce the need for external inputs and decrease the use of non-renewable resources [2,3]. ASC include crops that positively influence agroecosystems (e.g., complementary crops, catch crops, cover crops, etc.) by providing or enhancing ecological functions, irrespective of their timing in crop rotation or the technique utilized to manage them [4]. Overall, European organic farmers strongly rely on mowing/chopping the ASC and incorporating the plant material into the soil by tillage (i.e., using it as green manure, ASC-GM) prior to growing the cash crop [5]. However, tillage is usually identified as one of the most energy-demanding inputs, and the adoption of less disturbing soil techniques is required to improve energy performance of

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Nomenclature

Agroecological service crops	ASC
No-till roller crimper	ASC-NT
Green manure	ASC-GM
Not using ASC, Bare soil	BS
Machinery energy	ME
Estimated energy of production for a machine	E
Weight of a machine	G
Economic life of a machine	T
Renewable energy inputs	RE
Non-renewable energy inputs	NRE
Marketable cash crop yield	MCY
Potentially recyclable energy	PRE
Energy use efficiency	EUE
Net energy	NE
Marketable energy ratio	MER
Energy recycling ratio	ERR
Principal component analysis	PCA
Total energy consumption	TE

cropping systems [6] and enhance the physical and biological quality of soil [7]. Conversely, the no-till roller crimper (ASC-NT), consisting of a steel drum with metal slats arranged in a chevron pattern, which flattens the ASC and creates a dense layer of plant residues [8], is still hardly used in organic commercial productions [5], and the available research focused on European agronomic conditions is still scarce.

A few studies, all of them conducted in Italy [9–11], have analysed the effect of ASC introduction and compared energy flows in organic vegetable systems under the two management strategies (ASC-GM and ASC-NT). Diacono et al. [9,10] pointed out that the introduction of ASC in the crop rotation required a higher number of mechanical operations than when not using ASC, implying higher machinery and fuel energy consumption. However, it is important to note that these studies accounted for neither the energy retained in the ASC nor that in the cash crop residues to analyse the efficiency of the vegetable cropping system.

Indeed, available scientific literature dealing with the energy retained in the cash crop residues is still scarce. To the extent of our knowledge, only Bojacá and Schrevens [12] and Alluvione et al. [6] have agreed on the importance of considering cash crop residues in the energy balance. Bojacá and Schrevens [12] compared the effect of the inclusion of vegetable cash crop residues in the output of energy efficiency indexes, concluding that the interpretation of energy balance can change if residues are considered. Alluvione et al. [6] highlighted the likely benefits of considering cash crop residues to enhance soil fertility for arable crops, potentially saving energy in terms of synthetic fertilizers. Nevertheless, these studies did not evaluate environmental performance in terms of the energy that could be recycled within a cropping system. Moreover, vegetable discarding resulting from rigorous food quality standards has an important impact on yield losses [13], which may also have relevance for energy balance. However, to the best of our knowledge, studies to date have neither included cash crop quality indicators in their energy analyses nor specified whether discarded yield of cash crops was included within crop residues.

Therefore, it appears that available studies do not account for all the likely sources of energy that could be recycled (ASC, weeds, discarded yield and other residues of cash crops) within a cropping system, and, moreover, none of these investigations have evaluated the efficiency of cropping systems for recycling energy. To fill this knowledge gap, we gathered information from eight field experiments on organic vegetable systems in six European countries across different vegetable crops, soils and climatic conditions, over two years, with the aim to explore the effects of ASC introduction and management (ASC-GM and ASC-NT) on energy flows (inputs, removed outputs and energy recycled within the system) in contrast to the common strategy of not using ASC (Bare soil, BS). Moreover, we compared the production efficiency, the effects on cash crop quality and the environmental performance, in terms of energy flows, between ASC-NT and ASC-GM. However, most importantly to close the gap in understanding the efficiency of cropping systems for recycling energy, we propose the concept of Potentially Recyclable Energy (PRE) to account for all the energy contained in ASC, weeds and cash crop residues (including discarded yield and other plant residues) that can be recycled within a cropping system. This new concept provides insight on environmental performance of cropping systems. In this study, we explore the use of PRE both to evaluate the efficiency of cropping systems for transforming inputs into potentially recycling energy and to analyse the link between the marketable yield and the energy that can be potentially recycled.

2. Material and methods

2.1. Description of locations and management of trials

In this study, sixteen original datasets (i.e., eight field experiments each over two years) from six European countries involved in the SoilVeg (ERA-Net CORE-Organic Plus) project were analysed. Field experiments were conducted in Belgium (BE), Denmark (DK), Estonia (EE), France (FR), Italy (IT), and Spain (ES) (Table 1).

Field experiment type A (FtA) was carried out by all countries involved in this study (BE, DK, EE, FR, IT, ES) and entailed growth of ASC during autumn-winter (cold-rainy season) and transplantation of the cash crop during spring-summer. Field experiment type B (FtB) was established only in the Mediterranean countries IT and ES. In FtB, ASC were sown in the warm-dry season (i.e., summer) and the cash crop was transplanted at the end of summer or beginning of autumn.

The locations covered a wide range of agronomic conditions under different climatic zones of Europe [14]. In each country and trial, different environmental conditions, experimental designs, and cash crops were established (Table 1). However, all trials compared the energy inputs and outputs of three different organic vegetable management systems: two ASC management strategies i) ASC-NT in which ASC were flattened by roller crimper and narrow transplanting furrows were created by in-line tiller, ii) ASC-GM in which ASC were mowed/chopped and incorporated into the soil; and a strategy not using ASC, iii) BS, based on keeping the soil bare without any plant cover before vegetable cash crop transplantation. In each country and trial, different agronomic operations and timing were employed for ASC-GM and BS, depending on the local conditions and available machinery (Table 2). Conversely, the machinery used for ASC-NT management was similar among countries.

2.2. Computation of the energy inputs and outputs

In each field experiment, data on inputs and outputs were collected from the whole cropping cycles of the ASC/vegetable crops for each management strategy and year. Energy input included human labour, diesel consumption, electricity, water for irrigation, ASC seeds, cash crop plantlets, organic fertilizers and organic soil amendments (i.e., manure and commercial compost), crop protection inputs (i.e., insecticides, copper and sulphur), and

Table 1
Environmental conditions, cash crop, ASC, and factors analysed for each trial. FtA: Spring-summer cash crop; FtB: Autumn-winter cash crop. European Climatic Zones refer to Metzger et al. [14] classification. 1Y: first year, 2Y: second year of experimentation. ASC composition: L: Legumes; G: Grasses; B: Brassicaceae.

Country	Trial	European Climatic Zones	Temperature rainfall (annual mean)	Soil type	Cash crop	ASC composition	Explanatory variables in the models	Experimental design
Belgium	FtA	Atlantic Central	1Y: 898°C; 11.1 mm 2Y: 822°C; 11.3 mm	Sandy loam	White cabbage	L and G	Termination Total biomass Year	Split-split-plot randomized complete block design
Denmark	FtA	Atlantic North	1Y: 9.3 °C; 614 mm 2Y: 9.1 °C; 673 mm	Sandy loam	White cabbage	L and/or G	Termination Total biomass Year	Split-plot randomized complete block design
Estonia	FtA	Nemoral	1Y: 6.0 °C; 825 mm 2Y: 5.8 °C; 694 mm	Sandy clay loam	White Cabbage	L or G	Termination Total biomass Year Fertilization	Strip-plot randomized complete block design
France	FtA	Mediterranean North	1Y: 15,5°C; 521 mm 2Y: 15.3°C; 558 mm	Clay loamy	Butternut squash	L and/or G	Termination Total biomass Year	Randomized strip-plot
Italy	FtA	Mediterranean North	1Y: 16.7°C; 539 mm 2Y: 16.5°C; 402 mm	Clay	Tomato	L and G	Termination Total biomass Year Fertilization	Split-split-plot randomized complete block design
	FtB	Mediterranean North	1Y: 16.6°C; 470 mm 2Y: 16.7°C; 539 mm	Clay	Cauliflower	L and/or G and B	Termination Total biomass Year	Split-split-plot randomized complete block design
Spain	FtA	Mediterranean North	1Y: 16.5 °C; 406 mm 2Y: 16.1°C; 409 mm	Loamy	Green pepper	L and/or G	Termination Total biomass Year	Randomized strip-plot
	FtB	Mediterranean North	1Y: 16.1 °C; 344 mm 2Y: 16.5°C; 406 mm	Loamy	Cabbage	L and/or G	Termination Total biomass Year	Randomized strip-plot

Table 2
Description of the agronomic operations carried out in each trial. FtA: Spring-summer cash crop; FtB: Autumn-winter cash crop. 1Y: first year, 2Y: second year of experimentation. 2WD: Two-wheel drive tractor; 4WD: four-wheel drive tractor. ASC: Agroecological service crops. RC: Roller crimper. ILRC: RC + in-line tiller. RH: rotary harrow. MW: Mower.

Country	Soil preparation	ASC irrigation	Green manure termination	Roller Crimper termination	Plantation	Irrigation	Weeding	Fertilization	Harvest	Crop protection	Cash crop residues
Belgium	Farmyard manure application cultivator + chisel plough	No	2 WD + MW 2 WD + chisel plough	2 WD + RC 2 WD + ILRC	Planting machine	1Y: no irrigation 2Y: 2 irrigations manually	Mechanical + Manual	Fertilizer machine	Manual	*Bacillus thuringiensis*	Mulched with MW
Denmark	Plough	No	2 WD + MW 2 WD + RH	2 WD + RC 2 WD + ILRC	Planting machine	1Y: 2 times by sprinkler 2Y: no irrigation	Weed-brush-machine	Fertilizer machine	Manual	Insect net + *Bacillus thuringiensis*	MW + ploughing
Estonia	Solid cattle manure application + ploughing	No	2 WD + MW 2 WD + plough	2 WD + RC (2–4 times) 2 WD + ILRC	Manual	1Y: no irrigation 2Y: 1 irrigation manually	Manual	Mechanical	Manual		MW + ploughing
France	Subsoiling + RH	No	2 WD + MW 2 WD + RH	2 WD + RC 2 WD + ILRC	Manual	Drip irrigation	Manual	Fertilizer spreader	Manual		MW + ploughing
Italy	Plough	FtA: No FtB: Yes	4 WD + MW 4 WD + RH	4 WD + RC 4 WD + ILRC	Manual	Drip irrigation weekly	Manual	Manual	Manual	FtA: Copper + pyrethrum	MW + ploughing
Spain	Chisel plough	FtA: No FtB: Yes	4 WD + MW 4 WD + RH	4 WD + RC 4 WD + ILRC	Manual	Drip irrigation weekly	Manual	Manual	Manual		MW + ploughing

the machinery-embodied energy fraction estimated on the basis of the machinery weight and economic life. The energy use of the different systems was estimated by multiplying each input/output by its corresponding coefficient of equivalent energy, taken from the literature (Table 3). Tractor diesel consumption for each specific operation was measured according to the procedure suggested by Canali et al. [11]. The energy use from fossil fuel estimated from the equivalences in Table 3 accounted for diesel consumption and lubricant costs [15]. The energy inputs of manufacturing tractors and machinery were calculated using the following formula [16]:

$$\mathrm{ME} = \frac{\mathrm{E} \times \mathrm{G}}{\mathrm{T}} \tag{1}$$

where ME is the machinery energy (MJ h^{-1}), E is the estimated energy of production for a machine ($\mathrm{E} = 62.7\ \mathrm{MJ\,kg}^{-1}$), G is the weight of the machine (kg), and T is the economic life of a machine (h). The economic lives of tractors and machinery were obtained from several sources [6,17,23].

Energy inputs from manure, organic composted fertilizer, organic soil amendments, ASC seeds, cash crop plantlets, human labour and water for irrigation were classified as renewable energy inputs (RE), while non-renewable energy inputs (NRE) included machinery, fossil fuel, cash crop protection and electricity [16,24]. Nevertheless, fertilization by organic industrial composted fertilizer was considered to account for 6.8% of non-renewable energy inputs, because of industrial manufacture and the packaging processes [25].

Energy outputs of the three management strategies were classified into two main categories: i) marketable cash crop yield (MCY) (MJ ha^{-1}), defined as the cash crop yield that meets commercial quality standards based on external appearance; and ii) potentially recyclable energy (PRE) (MJ ha^{-1}), which includes non-marketable cash crop yield, cash crop residues and total ASC biomass (i.e., ASC and weeds). ASC and weed biomass were measured just before ASC termination.

2.3. Energy performance parameters

To achieve deeper insight into the two ASC management strategies, several energy performance parameters were calculated for ASC-NT and ASC-GM systems. The energetic efficiency of the management strategies was evaluated with energy use efficiency (EUE) and net energy (NE) calculations according to the following formulas [26]:

$$\mathrm{EUE} = \text{Energy output}\left(\mathrm{MJha}^{-1}\right)/\text{Energy input}\left(\mathrm{MJha}^{-1}\right) \quad (2)$$

$$\mathrm{NE}\left(\mathrm{MJha}^{-1}\right) = \text{Energy output}\left(\mathrm{MJha}^{-1}\right) - \text{Energy input}\left(\mathrm{MJha}^{-1}\right) \quad (3)$$

These energetic efficiency indicators quantify how efficient an agronomic system is in transforming inputs into outputs [17]. In our study, we applied the EUE and NE considering energy output as: i) MCY (MJ ha^{-1}) and ii) PRE (MJ ha^{-1}).

Table 3
Energy equivalents of the inputs and outputs of the three organic systems analysed.

Input and Output	Units	Energy equivalent (MJ $unit^{-1}$)	References
Input			
Human labour	h	1.96	[15]
Water for irrigation	m^3	0.63	[17]
Farmyard manure	kg	0.3	[15]
Compost	kg	1.908	[18]
Diesel	L	56.31	[15]
Electricity	kWh	11.93	[16]
ASC seeds	kg	14.7	[19]
Cash crop Plantlets	unit	0.2	[12]
Crop protection			
Insecticides	kg	237	[20]
Copper	kg	78.2	[21]
Sulphur	kg	7.1	[21]
Output			
Cash crop			
Pepper	t ha^{-1}	837.36	[22]
Pumpkin	t ha^{-1}	1884.06	[22]
Cabbage	t ha^{-1}	1130.436	[22]
Tomatoes	t ha^{-1}	753.624	[22]
Cauliflower	t ha^{-1}	1046.7	[22]
ASC biomass	kg	0.3	[21]
Cash crop residues	kg	0.3	[21]

We also compared the quality performance of the cash crop production in terms of energy. To this end, we propose the marketable energy ratio (MER) indicator, which is computed as the ratio between the marketable cash crop yield (MJ ha^{-1}) and the total cash crop yield (MJ ha^{-1}):

$$\mathrm{MER} = \text{Marketable cash crop yield}\left(\mathrm{MJha}^{-1}\right)/\text{Total cash crop yield}\left(\mathrm{MJha}^{-1}\right) \quad (4)$$

In addition, we propose the energy recycling ratio (ERR) indicator, which quantifies the potentially recyclable energy per unit of marketable cash crop energy output:

$$\mathrm{ERR} = \text{potentially recyclable energy}\left(\mathrm{MJha}^{-1}\right) \times /\text{Marketable cash crop yield}\left(\mathrm{MJha}^{-1}\right) \quad (5)$$

2.4. Statistical analyses

2.4.1. Principal component analysis to evaluate energy inputs and outputs

Principal component analysis (PCA) was performed to explore the similarities and differences among ASC-NT, ASC-GM and BS in terms of energy inputs and outputs. The PCA was performed using the multivariate data analysis package FactoMineR [27] of the R statistical programming language [28], and the Factoextra package [29] was used to visualize the results.

As not all the energy input items are present in the observed treatments (i.e., electricity, crop protection), we used the following aggregated energy input categories as energy inflow variables in the PCA: i) the total energy consumption (TE); ii) the RE and iii) the NRE. MCY and PRE were considered as energy outputs for the quantification of the removed and recycled outflow variables, respectively. The data were scaled to unit variance before the analysis to prevent variables with high values from dominating.

2.4.2. Meta-analytic approach to compare energy performance parameters between ASC-NT and ASC-GM

Energy performance parameters were used to compare the two ASC management strategies. To this end, we did not merge raw datasets provided by the different partners, because of differences in the experimental designs, factors analysed and management (Tables 1 and 2). Instead, we used a meta-analytic approach [30] to test a common effect of ASC-NT (in comparison to ASC-GM) on the energy efficiency indexes across trials.

First, we constructed a statistical model for each indicator and trial, which included the comparison ASC-NT *vs* ASC-GM, along with all the other factors analysed in each trial (Table 1). Except for ES, the comparison between ASC management strategies was analysed for each partner and year with linear mixed-effects models. For each trial, we established the random effects according to the experimental design (Table 1). The experimental design of ES was strongly determined by the machinery traffic between plots, and thus, to account for the lack of independence between samples, we used spatial correlation structures in the models [31].

We compared, with likelihood ratio tests and Akaike's Information Criterion (AIC), models with different spatial correlation structures and a model without spatial correlation structure to determine the best option in each case.

Data were transformed when needed to meet the requirements of normality and homoscedasticity of residuals. We utilized R software [28] for all the statistical analyses; linear mixed-effect models were performed with the lme function of the R nlme package [32], while the gls function was used for models with spatial correlation structures.

Then, we utilized the weighted Stouffer's test to combine the P-values and to assess a common hypothesis across trials:

$$p_Z = 1 - \Phi\left(\frac{\sum_{i=1}^{k} w_i Z_i}{\sqrt{\sum_{i=1}^{k} w_i^2}}\right) \tag{6}$$

where $Z_i = \Phi^{-1}(1 - p_i)$, p_i is the P-value from the i-th study out of k studies in total, w_i is the weight selected for the study, and Φ and Φ^{-1} are the standard normal cumulative distribution function and its inverse. For this study, we weighted the Z_i by the standardized effect size, as suggested by Zaykin [30]:

$$w_i = \frac{|\mu_i|}{SE_i} \tag{7}$$

where μ_i is the coefficient estimate and SE_i is its standard error. For testing the same alternative hypothesis, individual P-values were converted to one-sided before combining as follows [30]:

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

We combined the data from the two consecutive years in each trial to analyse the effect of the termination in each trial to achieve the independence between P-values required for the weighted Z-test.

3. Results

3.1. Features of energy inputs across trials

Systems that included ASC in their crop rotation increased total energy inputs, on average, by 19.73% compared with BS. The evaluated systems required on average a total energy input of 32200.4 MJ ha^{-1} with ASC-GM management, 29379.3 MJ ha^{-1} with ASC-NT and 26495.2 MJ ha^{-1} with BS. The mean across trials showed that ACS-GM and ASC-NT increased the total energy inputs by 23.9% and 15.56% compared with BS, respectively. Concretely, ASC-GM required higher energy inputs than did BS in all the trials evaluated, while its input requirements were also higher than those of ASC-NT in all trials except for EE-FtA, where the trend was opposite (Table 4). ASC-NT exhibited higher energy inputs than did BS in six out of eight trials; conversely, in FR-FtA and BE-FtA, ASC-NT reduced the input requirements compared with BS (Table 4).

Considering all the cropping systems and trials evaluated, our study showed that fossil fuel was the highest energy input and represented, on average, 30.93% of the total inputs (Table 4). The second highest energy input was the energy of the cash crop plantlets, which reached, on average, 20.56% of the total input. Fertilizer was the third input in order of importance and accounted for the 17.21% of the total share. Conversely, the lowest share was crop protection inputs (1.53%) and water for irrigation (4.41%).

Particularly, machinery manufacturing input was increased, on average, by 31.2% in ASC-GM and by 17.5% in ASC-NT compared with BS. Similarly, fossil fuel input was increased, on average, 38.2% and 15.5% in ASC-GM and ASC-NT compared with BS, respectively. Conversely, human labour was reduced 5.1% and 19.2% in ASC-GM and ASC-NT in comparison with BS, respectively. The energy included in the seeds of the ASC systems comprised, on average, 9.15% of the total input.

The renewable energy ratio varied widely among trials. EE-FtA had the highest mean ratio (i.e., 70%), while BE-FtA showed the lowest value (i.e., 30%) (Table 4). Overall, the largest part of the total energy input was attributed to renewable energy (i.e., 52.67%).

3.2. Evaluation of the different management systems in terms of energy flow

The first three dimensions of the PCA (Fig. 1) explained 90.5% of the total variance. Specifically, the first component explained 47.6% of the variance and was defined by an efficiency in the use of the energy inputs. In fact, TE (Table 5) was the variable that contributed the most to the first component (38%) and that showed the highest positive correlation value with the axis (0.96). The second component of the PCA explained 26.2% of the overall variance and was defined by environmental effectiveness. The variables most influencing the second component were NRE (37.7%) and RE (33.7%), which showed, respectively, a negative (−0.68) and a positive (0.66) correlation. Furthermore, a large significant positive correlation was found with PRE (0.57). Last, the third PCA component explained 16.7% of the total variance. This third component distinguished the systems characterized by greater removed energy outputs, as it is strongly associated with MCY, which showed a contribution of 50.5% and a positive correlation of 0.65.

3.3. Energy performance parameters of the ASC management strategies

The results of the meta-analysis across trials showed that the ASC management strategy significantly affected the energy flow within the cropping systems. MCY-EUE was significantly reduced under ASC-NT compared with ASC-GM across trials, according to the weighted Stouffer's test (Table 6). Specifically, ASC-NT significantly reduced the MCY-EUE in four (DK-FtA, EE-FtA, ES-FtB, FR-FtA) out of the eight trials. However, opposite results were observed in ES-FtA and IT-FtA, where MCY-EUE was significantly higher under ASC-NT management. MCY-NE was significantly reduced under ASC-NT management, according to the results of the meta-analysis across trials (Table 6). Specifically, MCY-NE was significantly reduced under ASC-NT in three out of six trials included in the meta-analyses, while only in the ES-FtA trial did it increase significantly under ASC-NT.

Table 4
Average of the energy inputs (MJ ha^{-1}) of the three systems analysed by trial. The number between parentheses indicates the share for a specific system and trial. RE ratio: Renewable energy inputs ratio. DK: Denmark, EE: Estonia, ES: Spain, FR: France, and IT: Italy. FtA: Spring-summer cash crop; FtB: Autumn-winter cash crop. BS: Not using ASC, Bare soil; ASC-NT: roller crimper; ASC-GM: green manure.

Country	Trial	System	Machinery	Fossil fuel	Human	Fertilizer	ASC seeds	Cash crop Plantlets	Water	Crop protection	Electricity	Total Energy inputs	RE ratio
BE	FtA	BS	10109 (27)	17456 (46.7)	604 (1.6)	708 (1.9)		8163 (21.8)	161 (0.4)	196 (0.5)	0 (0)	37397	0.26
		ASC-GM	10491 (23.9)	20835 (47.4)	615 (1.4)	708 (1.6)	2756 (6.3)	8163 (18.6)	161 (0.4)	196 (0.4)	0 (0)	43925	0.29
		ASC-NT	8576 (24.8)	13796 (40)	236 (0.7)	708 (2.1)	2756 (8)	8163 (23.7)	80 (0.2)	196 (0.6)	0 (0)	34511	0.35
DK	FtA	BS	4654 (21.1)	6659 (30.2)	676 (3.1)	2198 (10)		7500 (34.1)	275 (1.2)	56 (0.3)	0 (0)	22018	0.48
		ASC-GM	5219 (18.8)	9249 (33.2)	697 (2.5)	2198 (7.9)	2624 (9.4)	7500 (27)	275 (1)	56 (0.2)	0 (0)	27818	0.47
		ASC-NT	5832 (21.8)	7517 (28.1)	779 (2.9)	2198 (8.2)	2624 (9.8)	7500 (28)	275 (1)	56 (0.2)	0 (0)	26782	0.49
EE	FtA	BS	207 (1.1)	4908 (25)	5367 (27.3)	1152 (5.9)		8000 (40.7)	0.4 (0)	0 (0)	0 (0)	19635	0.74
		ASC-GM	283 (1.2)	6415 (28)	5372 (23.4)	1152 (5)	1727 (7.5)	8000 (34.9)	0.4 (0)	0 (0)	0 (0)	22950	0.71
		ASC-NT	270 (1.1)	8500 (33.7)	5567 (22.1)	1152 (4.6)	1727 (6.8)	8000 (31.7)	0.4 (0)	0 (0)	0 (0)	25216	0.65
ES	FtA	BS	307 (0.8)	5180 (14.1)	1945 (5.3)	10812 (29.3)		5000 (13.6)	2835 (7.7)	0 (0)	10770 (29.2)	36849	0.54
		ASC-GM	394 (1)	5122 (12.8)	1948 (4.9)	10812 (27)	3124 (7.8)	5000 (12.5)	2835 (7.1)	0 (0)	10770 (26.9)	40005	0.58
		ASC-NT	276 (0.7)	3160 (8.4)	1487 (4)	10812 (28.9)	3124 (8.3)	5000 (13.3)	2835 (7.6)	0 (0)	10770 (28.7)	37464	0.60
	FtB	BS	610 (2.7)	8542 (37.4)	788 (3.4)	6360 (27.9)		5000 (21.9)	319 (1.4)	0 (0)	1212 (5.3)	22830	0.54
		ASC-GM	678 (2.1)	15162 (48)	496 (1.6)	6360 (20.1)	2181 (6.9)	5000 (15.8)	488 (1.5)	0 (0)	1212 (3.8)	31576	0.45
		ASC-NT	407 (1.3)	14654 (47.6)	453 (1.5)	6360 (20.7)	2181 (7.1)	5000 (16.3)	488 (1.6)	0 (0)	1212 (3.9)	30755	0.46
FR	FtA	BS	1028 (3)	16429 (48)	1372 (4)	8288 (24.2)		2000 (5.8)	2540 (7.4)	0 (0)	2580 (7.5)	34237	0.37
		ASC-GM	1106 (2.9)	17657 (46.6)	1410 (3.7)	8288 (21.9)	2303 (6.1)	2000 (5.3)	2540 (6.7)	0 (0)	2580 (6.8)	37885	0.40
		ASC-NT	848 (2.9)	9914 (33.6)	998 (3.4)	8288 (28.1)	2303 (7.8)	2000 (6.8)	2540 (8.6)	0 (0)	2580 (8.8)	29471	0.50
IT	FtA	BS	1057 (5.2)	4040 (19.9)	921 (4.5)	5819 (28.7)		5000 (24.7)	1985 (9.8)	1138 (5.6)	319 (1.6)	20280	0.64
		ASC-GM	1736 (5.7)	6667 (21.9)	807 (2.7)	5819 (19.1)	6956 (22.9)	5000 (16.4)	1985 (6.5)	1137.5 (3.7)	319 (1)	30427	0.63
		ASC-NT	1841 (6.3)	5349 (18.4)	654 (2.3)	5819 (20)	6956 (23.9)	5000 (17.2)	1985 (6.8)	1138 (3.9)	319 (1.1)	29061	0.66
	FtB	BS	940 (5)	3899 (20.8)	701 (3.7)	4894 (26.1)		4444 (23.7)	2019 (10.8)	1493 (8)	325 (1.7)	18716	0.62
		ASC-GM	1741 (7.6)	6526 (28.4)	706 (3.1)	4894 (21.3)	868 (3.8)	4444 (19.3)	2019 (8.8)	1493 (6.5)	325 (1.4)	23017	0.54
		ASC-NT	1748 (8)	5209 (23.9)	774 (3.6)	4894 (22.5)	868 (4)	4444 (20.4)	2019 (9.3)	1493 (6.9)	325 (1.5)	21775	0.58
Mean Share Percentage			8.17	30.93	5.69	17.21	9.15	20.56	4.41	1.53	5.39		

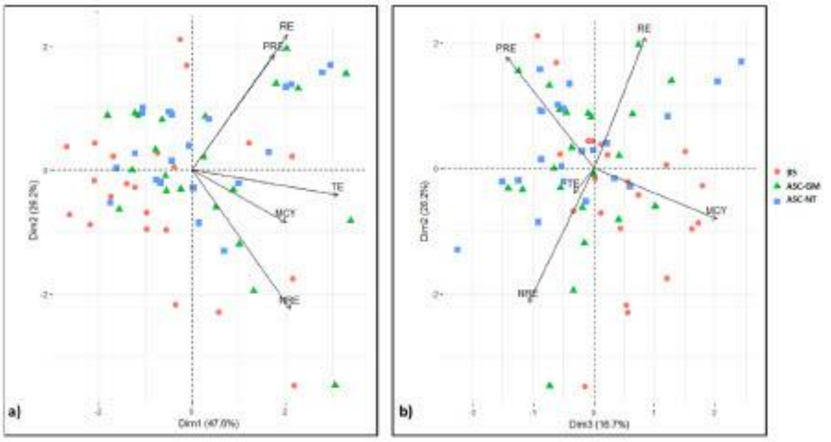

Fig. 1. Biplots of the first three dimensions (Dim) of principal components (Dim 1 & 2: panel a; Dim 2 & 3: panel b) from all systems (BS = Bare soil; ASC-GM = Green Manure; ASC-NT = No-Till roller crimper) and the energy input and output variables: Total energy (TE); Renewable energy (RE); Non-renewable energy (NRE); Marketable energy yield (MCY); Potentially recycling energy (PRE).

Table 5
The contributions - contr and the significant correlations - corr (*: significant at $P \leq 0.05$; **: $P \leq 0.01$; ***: $P \leq 0.001$.) of energy variables with first (Dim1), second (Dim2) and third (Dim3) principal components. TE: total energy; RE: renewable energy; NRE: non-renewable energy; MCY: marketable energy yield; PRE: potentially recycling energy.

	Dim1		Dim2		Dim3	
	contr (%)	corr	contr (%)	corr	contr (%)	corr
TE	38.4	0.96***	1.2	–	1.3	–
NRE	17.3	0.64***	35.7	−0.68***	14.1	−0.34**
RE	16.5	0.62***	33.7	0.66***	8.8	0.27*
MCY	15.8	0.61***	5.1	−0.26*	50.5	0.65***
PRE	12.1	0.54***	24.4	0.57***	25.3	−0.46***

MER was significantly reduced under ASC-NT in comparison with ASC-GM across trials (Table 6). Four of five trials in which this measure could be analysed followed the general trend, but the reduction was significant only in ES-FtB.

Conversely, the results of the weighted Stouffer's test showed significant increases in PRE-EUE, PRE-NE and ERR under ASC-NT compared with ASC-GM (Table 6). PRE-EUE increased in four out of eight trials, and this index was significantly reduced only in IT-FtB. PRE-NE was significantly increased in six out of seven trials under ASC-NT management; only in EE-FtA the trend was significantly negative.

4. Discussion

4.1. Features of energy inputs across trials

The analysis of energy consumption emphasized that the most relevant energy inputs were fossil fuel, cash crop plantlets and fertilizers, within the organic vegetable management systems analysed in this study. Our findings confirmed the results of several studies on vegetable production, which identified fertilization and fuel for mechanical operations as the inputs requiring the most energy [9,10,12,16]. Nonetheless, in our study the energy required for the cash crop plantlets represented the second most important input. Therefore, our findings indicate that greater consideration must also be given to the process of crop plantlet nourishment to increase the energy efficiency of cropping systems, confirming the results reported by Bojacá and Schrevens [12].

Considering the total energy inputs of the three evaluated management strategies, this study suggests that, in spite of the potential benefits that ASC provides to an agroecosystem [2,3], their introduction and management requires a higher energy investment than not using them. The greater input consumption in ASC management strategies was mainly related to ASC seeds and an increase in fossil fuels and machinery inputs compared with not using ASC. However, it is important to note that human labour was reduced under ASC management strategies compared with BS, mainly due to a lower number of weed control operations required. Conversely, previous studies conducted in Italy reported opposite results to the general trend observed in our study. Diacono et al. [9], measured energy input reductions in ASC-GM and ASC-NT when these treatments were compared to the fallow control (equivalent to bare soil), whereas Diacono et al. [10] noticed that ASC-GM required more energy inputs, while ASC-NT required slightly less than the fallow control. However, in these studies, the lower total energy consumption reported in ASC management strategies is related to the lower amount of N fertilization, rather than to reductions in fossil fuel, human labour, and mechanization requirements.

Table 6
Estimates (±standard error) and their *P*-values from the models testing the effect of ASC-NT management compared to ASC-GM on energy performance parameters for each trial, and results of the Weighted Stouffer's test for each energy performance parameter across trials. DK: Denmark, EE: Estonia, ES: Spain, FR: France, and IT: Italy. FtA: Spring-summer cash crop; FtB: Autumn-winter cash crop. MCY-EUE: marketable cash crop yield energy use efficiency; MCY-NE: marketable cash crop yield net energy; MER: marketable energy ratio; ERR: energy recycling ratio; PRE-EUE: potentially recyclable energy use efficiency; PRE-NE: potentially recyclable net energy. ASC-NT: roller crimper; ASC-GM: green manure.

		MCY-EUE		MCY-NE		MER		ERR		PRE-EUE		PRE-NE	
Country	Trial	Estimate ±SE	*P*-value	Estimate ±SE	*P*-value	Estimate ±SE	*P*-value	Estimate ±SE	*P*-value	Estimate ±SE	*P*-value	Estimate ±SE	*P*-value
BE	FtA	0.042 ± 0.204	0.8423	7295.0 ± 8540.4	0.4152	*NA*		*NA*		0.373 ± 0.06[a]	**0.0002**	2511.6 ± 477.9	**0.0008**
DK	FtA	−0.174 ± 0.033[b]	**0.0064**	*N*		*N*		0.971 ± 1.118[c]	0.4490	0 ± 0.003	0.8751	*N*	
EE	FtA	−0.193 ± 0.065[b]	**0.0052**	−5826.6 ± 1663.0	**0.0012**	−0.217 ± 0.133	0.1125	2.692 ± 2.457	0.2837	−0.008 ± 0.009	0.3971	−2619.5 ± 1117.4	**0.0247**
ES	FtA	0.138 ± 0.052	**0.0134**	5540.5 ± 2030.7	**0.0111**	0.008 ± 0.014	0.5837	−0.013 ± 0.009	0.1492	0.019 ± 0.008	**0.0176**	3151.3 ± 413.3	**<0.0001**
ES	FtB	−0.339 ± 0.104	**0.0022**	−10115.1 ± 3234.9	**0.0033**	−0.176 ± 0.057	**0.0040**	0.734 ± 0.257[a]	**0.0069**	0 ± 0.003	0.8865	166.2 ± 73.6	**0.0295**
FR	FtA	−0.437 ± 0.105	**0.0060**	−16960.6 ± 3107.1	**0.0016**	−0.009 ± 0.015	0.5754	0.039 ± 0.01	**0.0085**	0.02 ± 0.002[a]	**0.0001**	8162.3 ± 289.2	**<0.0001**
IT	FtA	0.367 ± 0.148[a]	**0.0310**	*N*		−0.022 ± 0.01	0.0532	−0.027 ± 0.01	**0.0151**	0.003 ± 0.001	0.0387	1422.6 ± 89.7	**<0.0001**
IT	FtB	−0.109 ± 0.074	0.1612	−1806.5 ± 1583.5	0.2689	*N*		−0.017 ± 0.042	0.6825	−0.017 ± 0.004	**0.0012**	709.6 ± 112.9	**<0.0001**
Stouffer test Hypothesis		ASC-NT < ASC-GM		ASC-NT < ASC-GM		ASC-NT < ASC-GM		ASC-NT > ASC-GM		ASC-NT > ASC-GM		ASC-NT > ASC-GM	
		Z	*P*-value	Z	*P*-value	Z	*P*-value	Z	*P*-value	Z	*P*-value	Z	*P*-value
		3.8287	**< 0.001**	4.008	**< 0.001**	3.7456	**< 0.001**	1.7395	**0.041**	4.7534	**< 0.001**	9.5577	**< 0.001**

N: Not a normal distribution; *NA*: not an evaluated parameter.
P-values below 0.05 are in bold.
[a] Logarithm transformation.
[b] Square-root transformation.
[c] Box-Cox transformation.

The comparison of both ASC management strategies demonstrates that ASC-NT reduced fossil fuel, machinery manufacturing and human labour inputs in comparison with ASC-GM across the six European countries included in our study, and this trend agrees with previous studies carried out in Italy [9–11]. Tillage operations used for incorporating ASC material into soil in ASC-GM required higher fossil fuel energy consumption than did flattening the ASC with roller crimper [10,11]. Moreover, the machinery utilized in ASC-GM usually required higher energy input investment for its manufacturing than that used under ASC-NT. Furthermore, the human labour reduction in ASC-NT was related to the lower number of operations demanded to manage ASC and lower weeding effort required during the cash crop cycle. Nonetheless, the extent to which human labour is reduced under ASC-NT management can be determined by the ASC biomass, the potential regrowth of the ASC and weed species, and the specific weather conditions of the year, which influence the type and frequency of agronomic operations required [9–11].

On the whole, in the three systems evaluated in our study, the total energy input was attributed to a greater extent to renewable energy sources (52.67%), contrasting with the outcomes obtained in most studies of conventional vegetable cropping systems available in the literature [12,16,17]. As fertilizer is one of the main inputs of vegetable cropping systems, the difference in use of renewable energy could be mainly referred to the nature of the fertilizers applied. In our study, the fertilizers were exclusively commercial organic compost and farmland manure, which are considered renewable sources, whereas in most of the available literature only synthetic fertilizers or a combination of organic and synthetic amendments were applied. Additionally, it is important to note that we did not observe important differences between the use of renewable sources in ASC management strategies and systems that did not include them.

4.2. Evaluation of the different management systems in terms of energy flow

Trials were characterized by different vegetable cropping systems and practices according to environment and local context. Nonetheless, the multivariate approach allowed us to distinguish the ASC management strategies from BS in terms of the most relevant energy variables.

Although there are no well-defined clusters, most of the BS observations have negative values along the first component and positive scores on the third. Consequently, BS was the most efficient market-oriented management system, characterized by lower energy inputs and higher correlation with the harvested energy outflows. This pattern has also been confirmed in other studies [10].

The ASC management strategies overlapped almost completely in the multivariate space, and they were not clearly distinguishable. Nevertheless, they tend to position in the positive side of the second dimension, highlighting a greater propensity for recycling energy outputs and for renewable energy utilization. Conversely, they showed reduced efficiency in terms of removed outputs, as they are also characterized by negative values on the third axis. Marketable yield losses linked to cover crops and conservative tillage implementation were also reported in other research studies investigating similar organic vegetable production systems [4,33].

However, few BS cases showed high environmental performance to be correlated with PRE. These cases are characterized by large amounts of cash crop residues, similar to the amounts of above-ground biomass of the residues produced by the cash and cover crops in the ASC management strategies.

PCA results indicate that the ASC management strategies are more correlated with environmental efficiency and with energy outflow recycling, while BS is more market oriented. However, PCA was not able to highlight the differences between the two ASC management strategies.

4.3. Energy performance parameters of the ASC based management systems

The results of the different organic vegetable pedo-climatic systems across Europe revealed that the selection of the ASC management strategy has a significant effect on the cash crop marketable production efficiency, the quality of the cash crop, and the environmental effectiveness of the organic vegetable cropping system. Although the results displayed some variability among trials, the set of experiments in different countries suggests that the adoption of ASC-NT management significantly reduces the cash crop marketable production efficiency and cash crop quality, but enhances the quantity of potential energy that can be recycled within the cropping system.

The increase in MCY-EUE is usually related to higher cash crop yields and/or lower energy input consumption [16], whereas MCY-NE is primarily determined by cash crop yields of a cropping system [6]. In our study, production efficiency indicators were reduced in ASC-NT mainly by the lower yield quality, as indicated by the significant reduction in the MER indicator. This issue might compensate for greater input consumption observed under ASC-GM. The lower marketable productivity and cash crop quality under ASC-NT may be explained by the nitrogen shortage under ASC-NT during cash crop development and growth [9,10,34]. Moreover, ASC management strategies might reduce fertilizer input, which was classified as the most relevant energy input. However, our experimental designs did not permit us to account for it. Thus, our results should be completed with studies accounting for the fertilizer reduction that can be achieved in ASC management strategies.

Despite the important implications that PRE can have in reducing the need for external inputs and reducing the use of non-renewable resources, no studies are available evaluating the environmental effectiveness of vegetable production systems. The only study focused on vegetable systems in which cash crop residues were measured concluded that energy balance interpretation can change if residues are considered; however, the authors do not evaluate the potentially recycling energy within a vegetable system [12]. Therefore, we report for the first time how PRE, proposed in this study, allows evaluation of a cropping system in terms of the potential efficiency of recycling energy within the system. In addition, higher values of indicators including PRE imply a greater retention and/or restitution of energy to an agroecosystem that is therefore stored in soil organic compartments, contributing to soil C sequestration and promoting favourable soil microbial heterotrophic processes [35]. Accordingly, soil quality may be enhanced and soil fertility capitalized over the long term, allowing future savings in energy and nutrient inputs. Our results indicate that the adoption of the ASC-NT management strategy can significantly increase environmental effectiveness by enhancing the efficiency of transformation of energy inputs into PRE and by increasing the proportion of PRE per unit of MCY compared with ASC-GM. However, is it important to note that the higher proportion of PRE observed under ASC-NT was related to the higher non-marketable yield, which may affect farmers' acceptance of this management strategy.

5. Conclusions

This study, which gathered information across six European countries and eight field experiments located at different latitudes and conducted in different seasons and crop cycles, indicates that

ASC introduction and management requires a higher input investment than the strategy that did not include ASC. Nonetheless, management strategies that introduced ASC in the crop rotation were more prone to enhance the environmental performance by increasing the recycling energy outflow than the strategy that did not use them, which were more market oriented.

Our study also reveals that the strategy selected to manage ASC determined the total energy required and the efficiency of a cropping system. Under ASC-NT, fossil fuel, machinery manufacturing and human labour inputs were reduced. Therefore, lower total energy input was required than under ASC-GM. Additionally, we showed, for the first time, that the adoption of ASC-NT significantly reduces the cash crop marketable production efficiency and crop cash quality but increases the potential energy that can be recycled within the cropping system across a wide range of European pedoclimatic conditions and vegetables crops. However, there is high variability in energy performance parameters that depends on the machinery used, the specific agronomic conditions, ASC species and the vegetable crop.

Notably, the inclusion of MCY and PRE indicators helps to evaluate the sustainability of both systems considering both the market orientation and the environmental effectiveness. Moreover, the concept of PRE highlighted the importance of recycling the non-marketable cash crop yield to increase the recycling potential of a cropping system.

Compliance with ethical standards

Conflict of interest

This manuscript has not been submitted to, nor is under review at, any other journal or publishing venue.

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The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

Authors' contributions

David Navarro-Miró contributed to the design of the work, collected and analysed the data, interpreted the results, and drafted the article. **Ileana Iocola and Alessandro Persiani** contributed to the design and management of the work and to drafting the article. **José M. Blanco-Moreno** contributed to the analysis of data, the interpretation of the results and the drafting of the article. **Hanne Lakkenborg Kristensen, Margita Hefner, Kalvi Tamm, Ingrid Bender, Hélène Védie, Koen Willekens, Mariangela Diacono, Francesco Montemurro, F. Xavier Sans** contributed to the design and management of the experiments and collection of data in each country. **Stefano Canali** (SoilVeg project coordinator) conceived the *trans*-national, multisite and multi-season dimensions of the entire experiment; had a major role in the conception and design of the work, interpreted the results and contributed to drafting the article. All the authors critically revised the final manuscript.

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Capítol 3. Gestió de cultius amb serveis agroecològics en sistemes hortícoles ecològics europeus: La importància d'avaluar aspectes agronòmics, ecològics i ambientals

Títol: Managing agroecological service crops in European organic vegetable systems: The need of evaluating agronomic, ecological and environmental performance

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Resum

Tot i que originalment es va promoure l'agricultura ecològica com a sistema agrícola alternatiu que incloïa aspectes agronòmics, ambientals i ecològics, la seva convencionalització ha comportat una intensificació i especialització de la producció. A la vista d'això, diversos estudis han posat en dubte els beneficis ambientals de l'agricultura ecològica, així com la seva viabilitat agronòmica. Per tant, és necessari re-dissenyar els sistemes hortícoles ecològics per millorar el seu acompliment ambiental sense afectar-ne la productivitat. Per afrontar aquest desafiament, les agricultores i agricultors, i investigadores i investigadors europeus recentment han començat a interessar-se amb els cultius amb serveis agroecològics (ASC). No obstant això, pocs estudis han avaluat simultàniament els aspectes agronòmics, ambientals i ecològics de la seva gestió en diferents condicions pedo-climàtiques europees.

En aquest estudi, es van avaluar els efectes de la gestió de l'ASC (NT-RC vs. la incorporació al sòl amb la llaurada) sobre el rendiment del sistema de cultiu mitjançant un conjunt d'indicadors agronòmics, ambientals i ecològics, per exemplificar la necessitat de l'anàlisi multidimensional per entendre les seves implicacions a l'hora d'afrontar reptes agronòmics i ambientals. Es va fer servir un enfocament meta-analític per combinar els resultats d'onze experiments hortícoles ecològics realitzats en set països europeus durant un període de dos anys.

Aquest estudi mostra les diferents implicacions des del punt de vista agronòmic, ambiental i ecològic de la gestió de l'ASC (NT-RC vs. la incorporació al sòl amb la llaurada). Els nostres resultats evidencien de manera sòlida, en diferents condicions pedo-climàtiques d'Europa, que la gestió dels ASC mitjançant el NT-RC millora la

densitat en activitat dels caràbids i estafilínids, millora tant el reciclatge d’energia potencial del sistema com el control de flora arvense. No obstant això, el NT-RC disminueix el rendiment del cultiu comercial i la seva qualitat, l'eficiència energètica de la producció i la densitat en activitat de les aranyes.

Per tant, els nostres resultats posen de manifest la necessitat d'avaluar simultàniament diferents aspectes agronòmics, ambientals i ecològics com a mitjà per proporcionar una visió més clara de l'efecte de la gestió ASC en el funcionament dels agroecosistemes. Es requereix encara més investigació per millorar el rendiment de NT-RC mitjançant l'ús de noves estratègies de fertilització durant el desenvolupament del cultiu i programes específics de millora vegetal. A més, s'haurien de dur a terme estudis econòmics per avaluar si els costos associats a la NT-RC compensen la reducció del rendiment i la qualitat del cultiu comercial.

Managing agroecological service crops in European organic vegetable systems: The need for evaluating agronomic, ecological, and environmental performance

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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 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, NT-RC decreases the cash crop yield and quality, the energetic efficiency of production, and the activity density of spiders.

Synthesis and applications: Multidimensional analyses using agronomic, environmental, and ecological indicators are required to understand the implications of agricultural management in agroecosystem functioning. Introducing ASCs combined with the use of NT-RC 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

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

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 that reduce productivity (e.g., pest damage), generate environmental issues (e.g., nutrient leaching), and affect both the maintenance and functioning of ecosystems and human well-being (Power, 2010; Zhang, Ricketts, Kremen, Carney, & Swinton, 2007).

In Europe, 1.9 % of arable land (2.2 million ha) is devoted to vegetable crops and produces approximately 65 million tonnes of fresh vegetables (De Cicco, 2016; EUROSTAT, 2019). Vegetables are the crops that need the highest energy input (Elsoragaby, Yahya, Mahadi, Nawi, & Mairghany, 2019) and, to ensure yields, vegetable production currently requires the greatest agrochemical input (i.e., fertilisers and pesticides) and the highest irrigation rates of all arable systems. Intensive management of these crops has caused environmental problems, including the notable consumption of non-renewable resources and nutrient leaching (Min, Zhang, & Shi, 2012; Torrellas et al., 2012) as well as health concerns derived from the presence of pesticide residues (González-Rodríguez, Rial-Otero, Cancho-Grande, & Simal-Gándara, 2008).

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

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

Another important constraint is related to the gap in crop yield between organic and conventional farming systems (Ponisio et al., 2015). Some studies argue that organic farming is less efficient as it requires more land to produce the same amount of food as conventional farming, and that more fossil fuel is required for weed control

(Trewavas, 2001, 2004). Additionally, under organic farming, the adoption of less intensive tillage management has been shown to potentially reduce the cash crop yield and fruit quality (i.e., the marketable parameters) (Ciaccia, Montemurro, et al., 2015; Diacono, Persiani, Fiore, Montemurro, & Canali, 2017). Fertilisation strategies based on the application of animal or green manure, as well as the recycling of energy and nutrients within the cropping system, are also argued to have potentially negative impacts on the environment (Trewavas, 2001, 2004). On the one hand, the process of manure decomposition and nutrient release from animal or green manure is not always well synchronised with the cash crop uptake. After the cash crop cycle, the manure remaining in the soil continues to decompose and release nutrients that can lead to nitrate leaching and the eutrophication of natural water bodies (Trewavas, 2001). On the other hand, Trewavas (2004) highlighted the fact that recycling energy and nutrients within the cropping system cannot compensate for the absorption of nutrients by the cash crop. Therefore, this type of management can lead to a progressive depletion of these nutrients in the soil.

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

Traditionally, European organic farmers have managed ASCs as green manure (T-GM) by chopping up and incorporating plant material into the soil by tillage (Peigné et al., 2016). However, as stated above, tillage can negatively affect the soil system. In recent years, therefore, the use of no-till roller crimping (NT-RC) for ASC management has attracted the interest of European farmers and researchers (Casagrande et al., 2016; Vincent-Caboud, Peigné, Casagrande, & Silva, 2017) because it can improve weed management and reduce dependence on tillage in organic farming. The roller-crimper flattens the ASC, creating a dense layer of plant residue on the soil surface (i.e., mulch) without soil disturbance. The use of NT-RC for ASC management originated in Brazil (Kornecki, Price, Raper, & Arriaga, 2009), and this approach has been studied and developed mainly in Latin America, Canada, and the USA (Altieri et al., 2011; Carr, Gramig, & Liebig, 2013; Delate, Cwach, & Chase, 2012; Shirtliffe & Johnson, 2012). The few studies performed in European organic vegetable systems have concluded that NT-RC reduces weed abundance dramatically and requires less fossil fuel than the T-GM approach (Canali et al., 2013; Ciaccia, Testani, et al., 2015; Diacono et al., 2017). Nevertheless, both positive and negative effects have been observed on cash crop yields when NT-RC is implemented under Mediterranean conditions (Canali et al., 2013; Ciaccia et al., 2016; Diacono et al., 2017). In addition, few studies have examined the impact of cover crop termination on beneficial soil fauna (Depalo et al., 2020; Magagnoli et al., 2018), root growth, and soil nitrogen (Hefner, Canali, et al., 2020; Hefner, Gebremikael, et al., 2020).

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

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

2. Material and methods

2.1. Locations and field trials

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

Two parallel field experiment types were carried out during two crop cycles as part of the SoilVeg project. Field experiment type A (FtA) was established at all trial locations (BE-ILVO, BE-INAGRO, BE-CRA-W, DK, EE, ES, FR, IT, SI) and involved the introduction of cold-rainy season ASCs into the crop rotation, followed by a spring-summer cash crop. The first FtA cycle took place during 2015 and 2016 and the second, during 2016 and 2017. Field experiment type B (FtB) was performed only at the IT and ES locations where the Mediterranean climatic conditions enabled introduction of the ASCs in the warm-dry season (i.e., summer) with irrigation, followed by the transplantation of an autumn-winter cash crop. The first FtB cycle took place during 2014 and 2015 and the second, during 2015 and 2016. In total, results from twenty-two original datasets were analysed (i.e., from 11 field experiments carried out over two years) (Table 1).

2.2. Trial management

All field trials were newly established. Both experiment types were repeated in the same plots during both years in ES and BE-ILVO, whereas in the other trial locations,

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.

new plots were established in adjacent areas of the same experimental field following a planned rotational design for the second year of experimentation. Notwithstanding different weather conditions, soil textures, ASC compositions, and experimental designs (Table 1), a comparison between the two ASC management strategies (NT-RC vs. T-GM) could be made for all trials. The NT-RC strategy involved: (1) ASC flattening by several roller crimper passages (2–4) to obtain a mulch of plant residue, and (2) the creation of a narrow transplanting furrow without disturbing the surrounding mulch using a slower in-line tiller. The T-GM strategy involved: (1) ASC mowing and/or chopping, (2) incorporation of the ASC pieces into the soil by tillage, and (3) preparation of the seedbed. Further information about the experimental design and agronomic management in each trial is provided in Appendix 1.

2.3. Cropping system performance indicators

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

2.3.1. Ecological and environmental indicators

We investigated the effects of ASC management on the soil system by analysing its impact on soil arthropod fauna and soil enzyme activity. We followed the concept of ecological indicators *sensu* McGeoch (1998) because the functions represented by these indicators are of significance to agriculture (Niemelä, 2000). The impact of the

ASC management strategies on the soil fauna was assessed by evaluating the activity density of ground (Carabidae) and rove (Staphylinidae) beetles and spiders (Araneae). These soil taxa have been shown to be sensitive to agricultural input and practices, including tillage, and are often used to typify the effect of agricultural practices on organisms living on the soil surface (Pretorius et al., 2018; Rivers et al., 2017). In each trial, soil arthropod activity density (AD) was calculated as the mean of the abundance of each taxonomic group in all samples divided by the number of traps and the number of days that traps were operative. The AD was normalised to seven days:

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

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

The effect of the ASC management strategy on soil quality was assessed using beta-glucosidase enzyme activity. This enzyme has known sensitivity to soil tillage, irrespective of pedo-climatic conditions, and can, therefore, provide rapid information regarding changes in soil properties (Ekenler & Tabatabai, 2003; Knight & Dick, 2004).

In the FtA trials, soil mineral nitrogen was measured at cash crop harvest as an indicator of the nitrogen leaching potential (N leaching). According to Hutchings and Kristensen (1995), it can be assumed that the remaining soil mineral nitrogen at the end of the growing season, which coincides with the beginning of the leaching season, will be leached during the winter. The potential recycling of material and energy within the cropping system was calculated using the concept of potentially recyclable energy (PRE) as an output of the cropping system in the energy-use efficiency indicator (PRE-EUE) (Navarro-Miró, Iocola, et al., 2019). The PRE incorporates all the energy that can potentially be recycled within a cropping system, including the energy contained in

ASCs, weeds, and cash crop residues (comprising discarded yield and other plant matter). The PRE-EUE indicator provides insight into the capacity of the cropping system to transform inputs into potentially recyclable energy. A description of the agronomic operations carried out in the evaluated trials, and the energy equivalents of the inputs and outputs used is provided in Navarro-Miró, Iocola, et al. (2019).

Further details of the procedures used to trap ground and rove beetles as well as the number and duration of sampling periods, beta-glucosidase enzyme activity determination, and the assessment of soil mineral nitrogen at harvest of the cash crop are provided in Appendix 2.

2.3.2. Agronomic indicators

We evaluated the effects of the ASC management strategies on two indicators: the cash crop marketable yield, and the cash crop quality. The cash crop marketable yield indicator was assessed using the dry biomass of the marketable cash crop yield, whereas the cash crop quality indicator included different measurements of the cash crop marketable parameters, as indicated in Appendix 2.

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

2.4. Statistical analysis

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

Statistical models for each partner were fitted according to the experimental variables evaluated and the experimental layout, and included all the experimental variables evaluated in each trial in order to rule out their effect on the dependent variable. The levels of the experimental variables included in each model are presented in Table 1. Total dry biomass (ASCs and weeds) was used as a covariate, calculated by pooling the different ASCs included in each trial and the weeds present prior to ASC termination.

For the BE-ILVO, BE-INAGRO, BE-CRA-W, DK, EE, FR, IT, and SI trials, we used linear mixed-effects models and defined random effects according to the specific experimental layout of each trial, as detailed in Table 1. However, for ES, given that the experimental layout was influenced by the need to facilitate the movement of machinery between plots, we introduced spatial correlation structures in the generalised linear models to account for the lack of independence between samples (Pinheiro & Bates, 2000). Thus, we established the best model for each dependent variable comparing different classes of spatial correlation structures as well as a model with no spatial correlation structure using likelihood ratio tests and Akaike's information criterion. Data were transformed when necessary to ensure the normality and homoscedasticity of the residuals (Tables 2 and 3). All statistical analyses were performed with R software (R Core Team, 2018). For linear mixed-effects models, we used the `lme` function of the R `nlme` package (Pinheiro, Bates, DebRoy, Sarkar, & R Core Team, 2017), except for BE-CRA-W and IT-N leaching and IT-beta-glucosidase enzyme activity models, for which we used the `lmer` function of the R `lme4` package (Bates, Mächler, Bolker, & Walker, 2015). For the IT trial, the AD of ground and rove beetles and spiders was analysed using the `glmer.nb` function of the `lme4` package (Bates et al., 2015). For the ES trial, we fitted the models with spatial correlation structures using the `gls` function. Then, the statistical significance of the effect of the management strategy on a specific indicator for all the trials was analysed using the weighted Z-test, which is essentially a weighted version of Stouffer's method, as in Zaykin (2011):

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

where $Z_i = \Phi^{-1}(1 - p_i)$; p_i is the *P*-value from the i-th study out of a total of k studies; w_i is the weight selected for the study; and Φ and Φ^{-1} are the standard normal cumulative distribution function and its inverse, respectively. For this study, we weighted *Zi* using the standardised effect size:

$$w_i = \frac{|\mu_i|}{SE_i}$$

where μ_i is the coefficient estimate, and SE_i is its standard error. To test for the same alternative hypothesis, individual *P*-values were converted to one-sided values before combining as follows:

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

Independence between *P*-values is required for the weighted Z-test. Thus, we analysed the data from the two consecutive years of each trial simultaneously and obtained the average effect of the termination strategy in each trial after taking into account the effect of the year.

3. Results

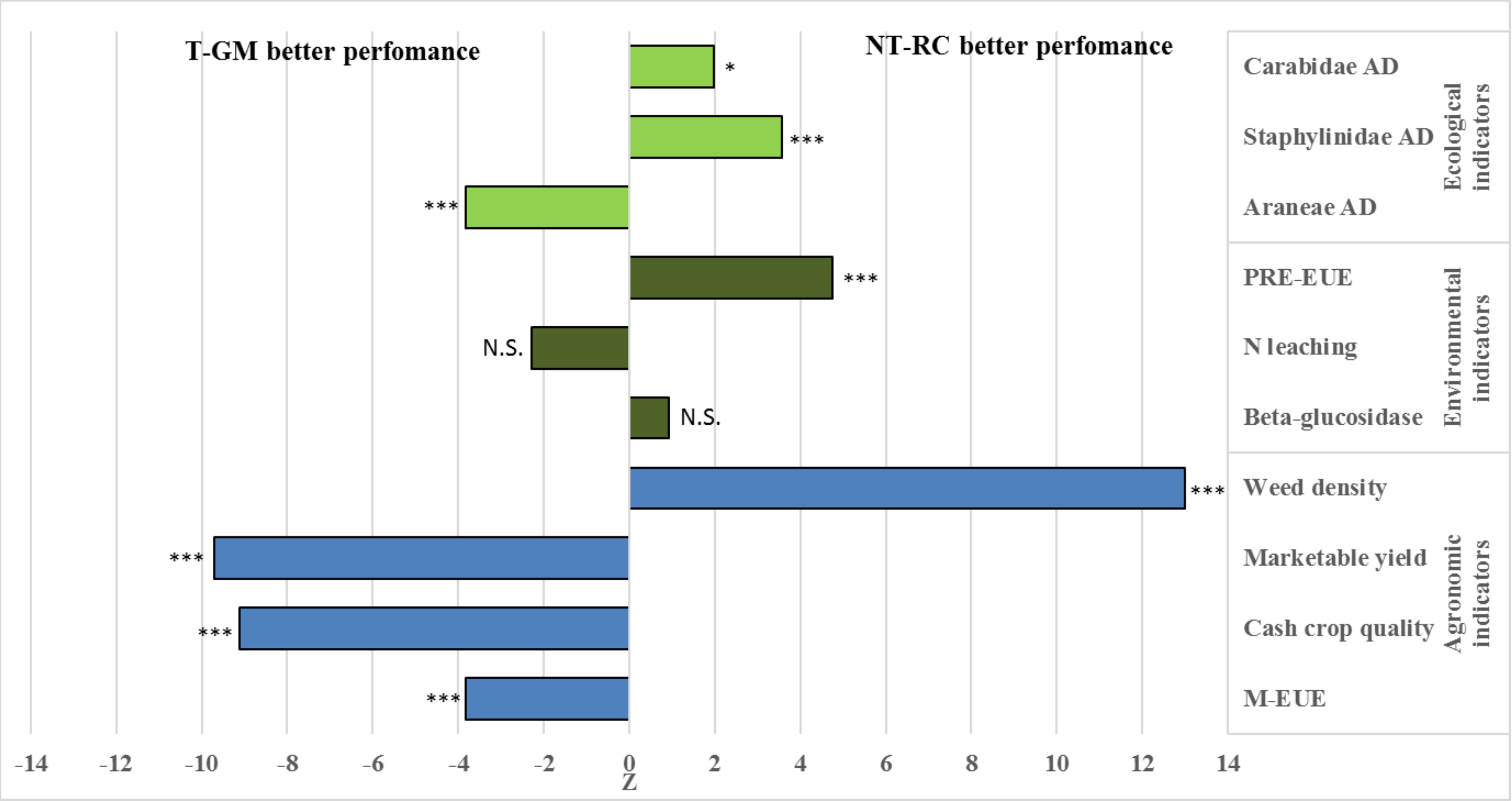
The results of the ranges (i.e., maximum and minimum) of the environmental, ecological, and agronomic indicators for each trial are presented in Appendix 3.

3.1. Environmental and ecological indicators

The meta-analysis showed that the ASC management strategy significantly affected soil arthropod AD and PRE-EUE (Figure 1), whereas it had no significant effect on the beta glucosidase indicators or N-leaching across the trials, except for the BE-CRA-W trial where the N leaching potential was significantly affected.

According to the weighted Stouffer's test, the Carabidae AD increased significantly under NT-RC compared to T-GM across the trials (Figure 1) except in SI-FtA under NT-RC where a significant decrease was observed (Table 2). The meta-analysis showed

Figure 1. Environmental and agronomic performance of T-GM and NT-RC. Graphical representation of the Z value obtained from the weighted Stouffer's test in trials for each indicator analysed. Significance codes: 'N.S.' P > 0.05; '*' P ≤ 0.05; '**' P ≤ 0.01; '***' P ≤ 0.001.



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

that Staphylinidae AD also increased significantly under NT-RC compared to T-GM (Figure 1). We observed a significant increase in Staphylinidae AD under NT-RC in IT-FtA and IT-FtB whereas in BE-ILVO-FtA and SI-FtA, the Staphylinidae AD decreased significantly (Table 2). Spider AD was lower under NT-RC than T-GM across the trials (Figure 1) and decreased significantly in two out of the five evaluated trials (Table 2).

The energy recycling efficiency of the ASC management strategies (evaluated using the PRE-EUE indicator) increased significantly across trials under NT-RC compared to T-GM (Figure 1). The PRE-EUE increased significantly under NT-RC in four out of eight trials, and decreased significantly only in IT-FtB (Table 2).

3.2. Agronomic indicators

All agronomic performance indicators were significantly affected by the ASC management strategy. Weed density under NT-RC was lower than under T-GM (Figure 1) and declined significantly in seven out of nine trials (Table 2). According to the meta-analysis, both yield descriptors (i.e., cash crop marketable yield and quality) decreased under NT-RC compared to T-GM (Figure 1). Similarly, the energy-use efficiency of the ASC management strategies evaluated using marketable yield as the output of the cropping system was lower under NT-RC compared to T GM (Figure 1), and showed significant decreases in four out of eight trials. However, energy use efficiency under NT-RC increased significantly in ES-FtA and IT-FtA (Table 2).

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

		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 *		
	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.
	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 *			

Country abbreviations as in Table 1. Ecological indicators: Carabidae AD: activity density of ground beetles; Staphylinidae AD: activity density of rove beetles; Araneae AD: activity density of spiders; Environmental indicators: PRE-EUE: energy-use efficiency using the potentially recyclable energy as the output of the cropping system; N leaching: nitrogen leaching potential

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

		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 *
	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 *
	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 ***			

Country abbreviations as in Table 1. Agronomic indicators: M-EUE: energy-use efficiency using the marketable yield as the output of the cropping system.

4. Discussion

The system comparison approach between NT-RC and T-GM shows the importance of multidimensional analysis for evaluating the advantages and disadvantages of agricultural practices from an environmental, ecological, and agronomic perspective before they can be promoted by advisors and policymakers, and implemented by organic vegetable farmers. Our results show that each of the ASC management strategies affected the performance of the agronomic, environmental, and ecological indicators differently.

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

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

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

Our NT-RC findings do not counter some of the main criticisms of this termination strategy regarding the yield and production efficiency of organic systems. Our results indicate that there is a consistent pattern of decreasing vegetable cash crop yield and marketable fruit quality under certain pedo-climatic conditions and crops. The reduction of the cash crop yield is one of the main drawbacks of no-till management, specifically when organic fertilisers are applied (Pittelkow et al., 2015). Overall, greater variability and lower cash crop yields are one of the factors hindering a more widespread adoption of no-till practices by European organic farmers (Casagrande et al., 2016; Vincent-Caboud et al., 2017). The negative effect of NT-RC on crop yield was related to limited N availability in the DK trial (Hefner, Gebremikael, et al., 2020). Similarly, other published literature links the yield gap and fall in marketable quality under NT-RC in organic vegetable systems to N shortages during cash crop development (Ciaccia, Montemurro, et al., 2015; Diacono, Persiani, Canali, & Montemurro, 2018; Diacono et al., 2017). Therefore, this line of evidence points to the need for improvement of fertilisation strategies to overcome this constraint in combination with the species chosen as the agroecological service crop as shown in the DK trial (Hefner, Canali, et al., 2020). Additionally, NT-RC was less efficient than T-GM in transforming inputs into marketable outputs. A reduction in M-EUE can be related to higher cash crop yields and/or lower energy input consumption (Mohammadi & Omid, 2010). In our study, the greater input consumption required by T-GM for tillage and weeding operations (Canali et al., 2013; Diacono et al., 2018) could be compensated by the higher yield and better quality observed with this management strategy.

Implementation of NT-RC improved the environmental performance in terms of the energy that could potentially be recycled within the cropping system. Flattening the ASCs and avoiding tilling prior to cash crop transplantation has been shown to increase the efficiency of the cropping system in terms of the potentially recyclable energy generated per unit of input invested (Navarro-Miró, Iocola, et al., 2019). Although future energy and nutrient input savings might result in the long term due to the higher retention of energy within the agroecosystem, the higher PRE observed in NT-RC plots was mainly caused by a higher non-marketable yield rate, which is not agronomically desirable. Therefore, more research is required to analyse whether the likely input savings would compensate the higher proportion of non-marketable yield observed under NT-RC in the long term. Regarding beta-glucosidase activity, no clear conclusion could be drawn in the short term from the findings of the present study. Similarly, the leaching of mineral N as a potential environmental indicator was only significantly affected by the ASC management strategies in one of five trials, and there was no common significant pattern across trials.

In this study, the response of agroecosystem functioning to the different ASC management strategies was evaluated immediately after their implementation.

However, longer-term studies are required to improve our understanding of the processes associated with organic NT-RC, and to evaluate whether this strategy is effective as a continuous long-term management approach.

5. Conclusions

In this study, we evaluated the consequences of a change in the management of organic vegetable production, from an agronomic, environmental, and ecological perspective. This study provides the first evidence that NT-RC enhances the AD of certain functional taxa (i.e., ground and rove beetles), the potential recycling of energy within the system, and early-season weed control in different vegetable crops and soils, and under different climatic conditions in Europe. However, compared to T-GM, NT-RC decreases the AD of spiders and the agronomic performance of the cropping system (i.e., cash crop yield and quality, and the energetic efficiency of cash crop production). Therefore, our results highlight the need to simultaneously evaluate different agronomic, environmental, and ecological aspects as a means of providing a clearer overview of the effect of ASC management strategies on agroecosystem functioning. Further research is thus required to determine how to reduce the yield gap under NT-RC via the use of new fertilisation strategies during cash crop development or in specific vegetable breeding programs. Additionally, studies performing economic analyses should be run to assess whether the costs associated with NT-RC compensate the reduction in cash crop yield and quality. Therefore, it is clear that for the promotion of any agricultural system, it is necessary to undertake a thorough analysis of a multi-faceted set of indicators.

Authors contributions:

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

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Compliance with ethical standards

Conflict of interest: The findings and conclusions expressed in this paper are those of the authors and do not necessarily reflect the views of the Spanish Ministerio de Educación, Cultura y Deporte, or any of the EU funding bodies. The authors declare that they have no conflicts of interest.

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Discussió general

Diversos estudis assenyalen que la introducció dels ASC poden influir positivament en el funcionament dels agroecosistemes i proveir serveis ecosistèmics (Schipanski et al. 2014; Robačer et al. 2016). No obstant, diversos autors assenyalen que la gestió de l'ASC afecta els serveis que proporcionen (Canali et al. 2013; Ciaccia et al. 2016). La majoria dels estudis que analitzen la gestió de l'ASC (deposició a la superfície del sòl amb el roller crimper, NT-RC vs. incorporació al sòl com adobs verds, T-GM) estan centrats en aspectes agronòmics i, en menor mesura, en l'acompliment ambiental, però no hi ha estudis que utilitzin un enfocament multidimensional mitjançant l'analisi simultània dels aspectes agronòmics, ambientals i ecològics. A més, la majoria dels estudis s'han realitzat en un context agronòmic, edàfic i climàtic determinat i en condicions experimentals específiques (és a dir, tipus de cultiu) que poden influir en els resultats obtinguts.

La discussió general d'aquesta tesi doctoral s'estructura en tres parts. En la primera part s'analitza l'efecte de la introducció dels ASC en els sistemes hortícoles ecològics sobre el flux d'energia mitjançant la comparació amb sistemes sense ASC (sòl nu, BS) en diferents condicions pedo-climàtiques a Europa. En la segona part es posa de manifest, per primera vegada, l'efecte del NT-RC sobre els paràmetres estructurals de les comunitats arvenses (densitat i riquesa d'espècies, i composició florística) (Capítol 1) i l'efecte sobre els fluxos d'energia (Capítol 2) en diferents cultius, sòls i condicions climàtiques en els sistemes hortícoles ecològics europeus. En la tercera part s'analitza l'efecte de la gestió de l'ASC sobre el funcionament dels sistema agrícola mitjançant un conjunt d'indicadors agronòmics, ambientals i ecològics, per exemplificar la necessitat d'un anàlisi multidimensional per comprendre els beneficis i els perjudicis de diferents pràctiques agrícoles des del punt de vista agronòmic, ecològic i ambiental (Capítol 3).

Finalment, es discuteix sobre les necessitats de recerca que sorgeixen després de la realització d'aquesta tesi doctoral.

1. Efecte de la introducció dels cultius amb serveis agroecològics en el sistema de cultiu

L'anàlisi de les aportacions energètiques totals de les tres estratègies de gestió avaluades (BS, T-GM, NT-RC) posa de manifest que incorporació i la gestió de l'ASC (T-GM i NT-RC) comporta una major inversió energètica que la no utilització (BS) (Capítol 2). El major consum d'energia en les estratègies de gestió que utilitzen ASC es relaciona principalment amb les llavors de l'ASC, l'augment dels combustibles fòssils i l'ús de maquinària en comparació amb la gestió sense ASC. No obstant això, és important tenir en compte que la mà d'obra es va reduir a les estratègies de gestió que van incloure els ASC en comparació amb BS, principalment a causa d'un menor nombre d'operacions de control de la flora arvense. Per la seva banda, els estudis anteriors realitzats a Itàlia van reportar resultats contraris a la tendència general observada en el nostre estudi. Diacono et al. (2017) van observar una reducció del consum d'energia en les estratègies de gestió que inclouen ASC en comparació amb el control (equivalent al sòl nu), mentre que Diacono et al. (2018) van constatar que T-GM tenia el major consum d'energia en comparació amb NT-RC i BS. Tanmateix, en aquests estudis, el menor consum d'energia total reportat en les estratègies de gestió que inclouen els ASC va estar relacionat amb la menor quantitat de fertilització de N, més que amb les reduccions del combustible fòssil, la mà d'obra i els requisits de mecanització.

Els resultats també posen de manifest que les estratègies de gestió que inclouen els ASC potencien els aspectes ambientals i ecològics del sistema, mentre que la gestió BS està més orientada a la producció del cultiu comercial (Capítol 2). Concretament, la gestió BS va ser la més eficient des del punt de vista de la producció ja que les aportacions energètiques són inferiors a la gestió amb l’ASC i la major part de l’energia extreta del sistema surt amb la collita del cultiu comercial. Aquest patró també ha estat constatat en altres estudis (Diacono et al. 2018). En contraposició, les estratègies de gestió que inclouen els ASC es caracteritzen per un potencial més gran per a reciclar l’energia i per a l’ús d’energies renovables, però son menys eficients en la transformació de l’energia en forma de collita del cultiu comercial (Capítol 2). La reducció del rendiment del cultiu comercial a causa de l’ús dels cultius de cobertura en el context de sistemes hortícoles ecològics basats en l’agricultura de conservació han estat també constatats per Leavitt et al. (2011) i Canali et al. (2015).

2. Impacte de la gestió dels cultius amb serveis agroecològics en el funcionament dels agroecosistemes

L'anàlisi conjunta dels resultats dels diversos experiments reflecteix que la introducció dels ASC en la rotació de cultius i la seva gestió amb NT-RC afecten significativament el funcionament del sistema de cultiu avaluat mitjançant un conjunt d'indicadors agronòmics, ambientals i ecològics. Els resultats globals indiquen que, malgrat la variabilitat entre experiments i països, l'adopció del NT-RC en comparació amb el T-GM millora el control de flora arvense (Capítol 1), el potencial reciclatge d'energia dins del sistema (Capítol 2) i la densitat en activitat de caràbids i estafilínids (Capítol 3). No obstant això, l'ús del NT-RC comporta la disminució de l'eficiència energètica de la producció (Capítol 2), el rendiment i la qualitat del cultiu comercial i la densitat d'activitat de les aranyes (Capítol 3) en comparació amb l'ús del T-GM, en els diferents cultius hortícoles, sòls i condicions climàtiques d'Europa.

2.1. Efecte de la gestió de cultius amb serveis agroecològics sobre composició de la comunitat arvense i els fluxos d'energia

Segons la literatura publicada, els arguments més comuns a favor de la gestió de NT-RC solen ser la millora del control de la flora arvense i la reducció dels requeriments energètics, mentre que l'inconvenient principal sol relacionar-se amb el rendiment del cultiu comercial (Canali et al. 2013; Ciaccia et al. 2015b; Diacono et al. 2017). Els nostres resultats, centrats en diferents cultius hortícoles i condicions pedo-climàtiques a Europa, posen de manifest el clar efecte de la gestió de l'ASC en els paràmetres estructurals de la flora arvense (densitat i riquesa d’espècies i composició florística de la comunitat arvense) (Capítol 1) i en els fluxos d’energia (Capítol 2).

2.1.1. Efecte de la gestió amb roller crimper sobre la densitat i la riquesa d’espècies arvenses, i la composició de la comunitat arvense

Els resultats confirmen que la gestió de NT-RC redueix significativament la densitat de la flora arvense als diversos experiments analitzats (Capítol 1). Els estudis duts a terme a Itàlia també assenyalen una reducció important de l'abundància de la flora arvense sota NT-RC en comparació amb T-GM (Canali et al. 2013; Ciaccia et al. 2016). El patró observat en el nostre estudi podria estar relacionat amb la presència de l’encoixinat que modifica la llum i la temperatura de la superfície del sòl (Teasdale i Mohler 2000; Canali et al. 2013), factors essencials que afecten el repòs i la germinació de moltes de les espècies arvenses (Guillemin et al. 2013; Batlla i Benech-Arnold 2014). L’eficàcia en el control de la flora arvense sota NT-RC en diferents condicions pedo-climàtiques a Europa reforça l’ús d’aquesta estratègia per gestionar la flora arvense en les primeres etapes del creixement dels cultius hortícoles per part de les agricultores i agricultors europeus. A més, aquesta estratègia afavoreix la reducció de la freqüència de la pertorbació del sòl en els sistemes hortícoles ecològics.

Aquests resultats proporcionen per primera vegada evidències solides de l’efecte significatiu de la gestió de l’ASC sobre la riquesa d’espècies i la composició florística de les comunitats arvenses en les etapes inicials dels cultius hortícoles ecològics (Capítol 1). Aquesta resposta immediata observada després de la gestió amb el NT-RC, divergeix de l'únic estudi disponible fins ara, en el qual es va observar una reducció significativa de la riquesa d’espècies arvenses al cinquè any de gestió continuada en cultius extensius de cereals (Halde et al. 2015). En general, s’han observat tant increments con disminucions de la riquesa de les espècies arvenses lligats a la intensitat de la llaurada (Armengot et al. 2015; Nichols et al. 2015) i la presència de l’encoixinat (Campiglia et al. 2010; Radicetti et al. 2013).

Els nostres resultats mostren que les comunitats arvenses varien de manera significativa en relació amb la gestió de l’ASC (NT-RC vs. T-GM) en la majoria dels experiments analitzats (Capítol 1). No obstant això, el percentatge de variabilitat de la composició de les comunitats arvenses atribuïble a la terminació fou generalment baix, i les comunitats arvenses estaven dominades per espècies anuals i de fulla ampla amb independència del tipus de gestió (Capítol 1). Estudis anteriors han reportat efectes de la intensitat de la llaurada (Armengot et al. 2015; Nichols et al. 2015) i la presència de l’encoixinat (Campiglia et al. 2010; Radicetti et al. 2013) sobre la composició de les comunitats arvenses. Tot i això, pel que sabem, només un estudi ha tingut en compte l'efecte del NT-RC sobre la composició florística de la comunitat arvense (Ciaccia et al. 2016). En aquest estudi, els autors especulen que el NT-RC podria influir en la composició de la comunitat arvense en sistemes de cultiu hortícoles ecològics, però no van comparar estadísticament les diferències entre la gestió NT-RC i la T-GM.

2.1.1.1 Importància relativa de la biomassa i la gestió dels cultius amb serveis agroecològics

La biomassa de l’ASC aplanada o trossejada i incorporada al sòl se sol considerar com un factor important per al control de la flora arvense (Radicetti et al. 2013; Canali et al. 2013; Ciaccia et al. 2016). Malgrat això, no hi ha estudis que analitzin la importància relativa de la biomassa de l’ASC, el tipus des gestió i, fins i tot, l’any sobre l’estructura i la composició de les comunitats arvenses en els cultius hortícoles ecològics. Els nostres resultats mostren que la importància relativa dels factors varia en funció del paràmetre estructural de les comunitats arvenses i de l’experiment analitzat (Capítol 1). Així, la importància relativa de la biomassa seca total abans de la terminació era baixa en tots els casos, malgrat l’amplia variació d’aquest factor entre experiments i la diferent proporció de la biomassa de la flora arvense en la biomassa total seca entre experiments, anys i països (Capítol 1). La gestió de l’ASC (NT-RC vs. T-GM) i les variacions en les condicions de cultiu (és a dir, l’any) van ser més importants que la biomassa produïda per explicar l’abundància de la flora arvense (Capítol 1). Així, els nostres resultats suggereixen que la reducció de la densitat de la flora arvense produïda per la gestió del NT-RC es pot veure fortament afectada per les variacions de les condicions de cultiu.

Alguns autors han suggerit que la composició de la comunitat arvense es veu afectada principalment per la intensitat de la llaurada, mentre que la riquesa específica és conseqüència tant de la gestió de l’ASC com de les condicions ambientals (Nichols et al. 2015). Els nostres resultats mostren que tant la composició de la comunitat arvense com la riquesa d'espècies varien en relació amb l'any i la gestió de l’ASC, i la seva importància relativa varia entre experiments (Capítol 1). No obstant això, l'any va tenir una importància relativa més gran en més experiments que la gestió de l’ASC, tant per a la riquesa d'espècies arvenses com per a la composició de la comunitat arvense. En canvi, la importància relativa de la biomassa seca va ser més baixa en la majoria dels experiments.

Per tant, el nostre estudi indica, per primera vegada, que les variacions en les condicions de cultiu poden afectar de manera significativa l’efecte de la gestió de l’ASC sobre els paràmetres estructurals de les comunitats arvenses (densitat i riquesa d’espècies, i composició de la comunitat arvense). A més, també posa de manifest que l'efecte de la biomassa seca total aplanada o incorporada al sòl és menys important que l'efecte tant de la gestió de l'ASC com de les condicions de cultiu sobre la densitat i la riquesa d'espècies, i la composició de la comunitat arvense per a la majoria dels experiments analitzats.

2.1.2. Efecte sobre els fluxos d’energia

2.1.2.1 Característiques dels inputs d’energia entre les estratègies de gestió dels cultius amb serveis agroecològics

La comparació de les dues estratègies de gestió dels ASC demostra que NT-RC redueix la necessitat de combustibles fòssils, l’energia requerida per a la fabricació de maquinària i la mà d'obra en comparació amb T-GM en diferents condicions pedo-climàtiques d’Europa (Capítol 2), i aquesta tendència coincideix amb estudis anteriors realitzats a Itàlia (Canali et al. 2013; Diacono et al. 2017, 2018). La pertorbació del sòl requerida per incorporar el material dels ASC al sòl en T-GM comporta un consum de combustible fòssil més elevat que no pas aplanar l’ASC amb el NT-RC (Canali et al. 2013; Diacono et al. 2018). La maquinària utilitzada en T-GM requereix una inversió energètica més elevada per a la seva fabricació que la que s'utilitza en NT-RC. A més, la reducció de la mà d’obra en NT-RC està relacionada amb el menor nombre d’operacions requerides per gestionar l’ASC i el menor esforç de desherbatge que es necessita durant el cicle de cultiu comercial (Capítol 2). Tot i això, la mesura en què es redueix la mà d'obra sota la gestió de NT-RC pot estar condicionada per la biomassa de l'ASC, el potencial de rebrot de l'ASC, les característiques de les espècies arvenses i les condicions meteorològiques específiques de l'any, que influeixen en el tipus i la freqüència d'operacions agronòmiques necessàries (Canali et al. 2013; Diacono et al. 2017, 2018).

2.1.2.2 Paràmetres d'acompliment energètic de la gestió dels cultius amb serveis agroecològics

Els resultats dels sistemes hortícoles ecològics localitzats en diferents condicions pedo-climàtiques d'Europa van revelar que la selecció de la estratègia de gestió dels ASC té un efecte significatiu en l'eficiència de la producció comercialitzable del cultiu comercial, la qualitat del cultiu comercial i l'acompliment ambiental del sistema de cultiu hortícola ecològic (Capítol 2). Tot i que els resultats van mostrar certa variabilitat entre els experiments, el conjunt d'experiments a diferents països suggereixen que l'adopció de la gestió de NT-RC redueix significativament l'eficiència de la producció comercialitzable dels cultius i la qualitat del cultiu comercial, però millora la quantitat d'energia potencialment reciclable dins del sistema de cultiu.

L'augment de MCY-EUE, indicador de l'eficiència en l'ús d'energia del sistema, està generalment relacionat amb uns rendiments més elevats del cultiu comercial i/o un menor consum d'energia (Mohammadi i Omid 2010), mentre que MCY-NE, que té en compte l'energia neta, depèn principalment dels rendiments del cultiu comercial (Alluvione et al. 2011). En el nostre estudi, els indicadors d'eficiència de la producció es van reduir en NT-RC principalment per la menor producció del cultiu comercial, tal com indica la important reducció de l'indicador MER, que correspon a relació entre el rendiment comercialitzable del cultiu comercial i el rendiment total del cultiu comercial (Capítol 2). Aquest aspecte podria compensar el major consum d’energia observat a T-GM. La menor productivitat comercial i la qualitat dels cultius comercials en NT-RC es pot explicar per l'escassetat en la disponibilitat de nitrogen en NT-RC durant el desenvolupament i creixement de cultius comercials (Ciaccia et al. 2015a; Diacono et al. 2017, 2018). No obstant, les estratègies que inclouen l’ús dels ASC podrien reduir l’entrada de fertilitzants, que es classifica com un dels inputs energètics més rellevants. Tot i això, els dissenys experimentals no ens van permetre analitzar aquest aspecte. Així, els resultats s'han de completar amb estudis sobre la reducció de fertilitzants que es pot assolir en les estratègies de gestió que inclouen l’ús dels ASC.

Malgrat les importants implicacions que pot tenir el PRE, l’energia potencialment reciclable associada al rendiment del cultiu hortícola no comercialitzable, els residus del cultiu i la biomassa de l’ASC i la flora arvense, en la reducció de la necessitat d’aportacions externes i la reducció de l’ús de recursos no renovables, no hi ha estudis disponibles que avaluïn l’eficàcia mediambiental dels sistemes de producció hortícoles. L’únic estudi centrat en sistemes hortícoles en què es van mesurar els residus de cultiu comercial va concloure que la interpretació del balanç energètic pot canviar si es consideren els residus del cultiu comercial; tanmateix, els autors no van avaluar l'energia potencialment reciclada dins del sistema hortícola (Bojacá i Schrevens 2010). Per tant, aquest estudi mostra per primera vegada com el PRE permet avaluar l'eficiència d’un sistema de cultiu en termes d'energia potencialment del reciclable (Capítol 2). A més, els valors més elevats d’indicadors que inclouen el PRE impliquen una major retenció i/o restitució d’energia en l’agroecosistema que s’emmagatzema als compartiments orgànics del sòl, i en conseqüència contribueix al segrest de C al sòl i promou els processos metabòlics dels microbis beneficiosos del sòl (Turmel et al. 2015). En conseqüència, la qualitat i la fertilitat del sòl es pot millorar a llarg termini, permeten futurs estalvis d'energia i aportacions de nutrients.

Els nostres resultats indiquen que l'adopció de l'estratègia de gestió NT-RC pot augmentar significativament els beneficis ambientals mitjançant la millora de l'eficiència de la transformació dels inputs d'energia en PRE i l'augment de la proporció de PRE per unitat de MCY en comparació amb T-GM (Capítol 2). Tot i que futurs estalvis d'inputs d'energia i nutrients poden resultar a llarg termini a causa de la major retenció d'energia dins de l'agroecosistema, l'augment del PRE observat a NT-RC va ser causat per una major proporció de rendiment no comercialitzable, cosa que no és desitjable agronòmicament. Per tant, es requereixen més investigacions per analitzar si el potencial estalvi d'inputs compensa la major proporció de rendiment no comercialitzable observada a NT-RC al llarg termini.

2.2. Efecte de gestió dels cultius amb serveis agroecològics sobre la fauna dels artròpodes del sòl, l'activitat dels enzims del sòl i la potencial lixiviació del nitrogen

La reducció de la llaurada i la creació d'un encoixinat amb el NT-RC van beneficiar la densitat en activitat dels caràbids i estafilínids (Capítol 3), que són generalment sensibles a la pertorbació del sòl (Tamburini et al. 2016; Rivers et al. 2017; Pretorius et al. 2018). Els nostres resultats coincideixen amb estudis previs sobre els efectes de la terminació dels ASC sobre la fauna del sòl (Magagnoli et al. 2018; Depalo et al. 2020). NT-RC redueix l'impacte directe de la llaurada (és a dir, les operacions d'incorporació dels ASC i de desherbat) sobre els organismes que habiten les capes més superficials del sòl (Roger-Estrade et al. 2010; Sommaggio et al. 2018) i pot crear condicions favorables (és a dir, refugis físics i provisió de preses) per a aquests grups durant el cicle de cultiu comercial (Sunderland and Samu 2000; Roger-Estrade et al. 2010). Aquests tàxons juguen un paper important en el funcionament dels agroecosistemes, ja que inclouen depredadors de plagues i llavors, i detritívors. Per aquests motius, la seva conservació i promoció pot millorar la prestació de serveis ecosistèmics (Pretorius et al., 2018).

En el nostre estudi, la densitat en activitat de les aranyes va disminuir sota el NT-RC en comparació amb T-GM (Capítol 3). Aquesta constatació contradiu el creixent nombre de treballs que indiquen els efectes positius de l’encoixinat (Sunderland i Samu, 2000) i la llaurada de conservació sense inversió de les capes del sòl (Tamburini et al., 2016) sobre l’abundància d’aranyes. La manca d’un patró clar entre la gestió de l’ASC i les poblacions d’aranyes posa de manifest la necessitat que es facin més estudis per millorar el coneixement de l’efecte de l’ASC aplanat sobre la macrofauna en funció de la mida del cos, el comportament i el rang de mobilitat (Jiménez-Valverde et al. 2010; Cardoso et al. 2011; Baatrup et al. 2018).

Tot i que els beneficis a llarg termini del PRE poden incrementar la qualitat i la fertilitat dels sòls, com es comenta a la secció anterior (“2.1.2. Efecte sobre els fluxos d’energia”, pàgina 64), no es va poder treure cap conclusió sobre l’activitat de la beta-glucosidasa a curt termini a partir de les conclusions del present estudi (Capítol 3). De la mateixa manera, la lixiviació del N mineral com a potencial indicador ambiental només es va veure afectada significativament per les estratègies de gestió de l’ASC en un dels cinc experiments i no hi va haver cap patró significatiu comú entre els experiments (Capítol 3).

2.3. Efecte de la gestió dels cultius amb serveis agroecològics sobre el rendiment i la qualitat del cultiu comercial

Els nostres resultats indiquen que hi ha un patró de disminució del rendiment i de la qualitat dels cultius comercials en determinades condicions pedo-climàtiques i cultius hortícoles (Capítol 3). La reducció del rendiment del cultiu comercial és un dels principals inconvenients de la gestió sense llaurada, concretament quan s'apliquen fertilitzants orgànics (Pittelkow et al., 2015). La major variabilitat i el menor rendiment dels cultius comercials són factors que impedeixen l’adopció més àmplia de les pràctiques de no-llaurada per part de les agricultores i agricultors ecològics europeus (Casagrande et al., 2016; Vincent-Caboud et al., 2017). L’efecte negatiu del NT-RC sobre el rendiment del cultiu comercial va estar relacionat amb la limitada disponibilitat de N a l’experiment de DK (Hefner et al. 2020b). De forma similar, altres estudis publicats vinculen la reducció del rendiment i la disminució de la qualitat dels cultius hortícoles ecològics sota el NT-RC amb l’escassetat de nitrogen durant el desenvolupament del cultiu comercial (Ciaccia et al. 2015a; Diacono et al. 2017, 2018).

3. Perspectives de recerca per a futurs estudis

En aquest estudi, s’ha analitzat la densitat i la riquesa d’espècies arvenses, i la composició de la comunitat arvense només en les primeres etapes del creixement dels cultius comercials (Capítol 1). Tot i això, algunes espècies arvenses poden germinar i rebrotar més tard en el cicle de cultiu a causa de canvis en condicions ambientals del sòl (Guillemin et al. 2013) i, en conseqüència podrien competir per l’aigua i els nutrients amb el cultiu i, fins i tot, causar problemes durant la recol·lecció d’alguns cultius hortícoles. Per això, aquesta avaluació s'ha de completar amb estudis que analitzin la emergència i el creixement de flora arvense durant el desenvolupament del cultiu comercial.

De la mateixa manera, l’efecte de la gestió de l’ASC sobre els fluxos d’energia (Capítol 2), la fauna del sòl, l’activitat enzimàtica del sòl, el potencial de lixiviació de nitrogen i el rendiment i la qualitat dels cultius comercials (Capítol 3) es van avaluar immediatament després de la seva implementació. Per aquest motiu, es requereixen estudis a llarg termini per millorar la comprensió dels processos associats ala gestió dels ASC en sistemes hortícoles ecològic mitjançant l’ús de NT-RC, i per avaluar si aquesta gestió pot ser implementada de forma continuada a llarg termini.

D’altra banda, la reducció de rendiment i la caiguda de la qualitat dels cultius comercials sota NT-RC en sistemes hortícoles ecològics sol estar relacionada amb l'escassetat de N durant el seu desenvolupament (Ciaccia et al. 2015a; Diacono et al. 2017, 2018). Per tant, aquesta línia d’evidències apunta a la necessitat de millorar les estratègies de fertilització.

Conclusions

La introducció dels cultius amb serveis agroecològics (ASC) en la rotació de cultius hortícoles es una de les estratègies àmpliament reconeguda per millorar la sostenibilitat dels sistemes. La terminació dels ASC abans de l'establiment dels cultius hortícoles permet proveir del nombrosos serveis ecosistèmics i evitar la competència amb els cultius posteriors. La gestió, més estesa, emprada per acabar l'ASC és la incorporació al sòl com adob verd mitjançant la llaurada (T-GM). Atès que la incorporació al sòl requereix molta energia, ma d'obra i pot tenir efectes negatius sobre el sòl, la deposició en superfície de l'ASC mitjançant el roller crimper (NT-RC) pot augmentar la sostenibilitat del sistema. No obstant, el coneixement científic actual encara no mostra evidències sòlides dels beneficis des del punt de vista agronòmic, ambiental i ecològic del NT-RC en diferents cultius, sòls i condicions climàtiques en els sistemes hortícoles ecològics europeus.

Per tal d'omplir aquest buit de coneixement, aquesta tesi doctoral pretén proporcionar una visió més detallada dels efectes del NT-RC en diferents condicions agro-edafo-climàtiques d'Europa, mitjançant l'anàlisi conjunta de les dades provinents d'experiments paral·lels durant dos anys en diversos països europeus en el marc del projecte SoilVeg (ERA-Net CORE-Organic Plus). També es va analitzar l'efecte de l'ús dels ASC en comparació a un tractament de control sense coberta del sòl (sòl nu, BS) des d'una perspectiva de balanç energètic.

A continuació, s'exposen les principals conclusions dels diferents estudis inclosos en aquesta tesi doctoral:

1. La introducció i gestió dels ASC en sistemes hortícoles ecològics requereix una inversió d'energia més elevada que no incloure'ls. No obstant això, la introducció dels ASC millora el funcionament dels sistemes des del punt de

vista ambiental i ecològic, mentre que la gestió sense ells està més orientada a la producció del cultiu comercial.

2. Aquest estudi proporciona per primera vegada una evidència sòlida de l'eficàcia de la gestió de l’ASC mitjançant l’estratègia basada en el NT-RC per al control de l’abundància i la diversitat de la flora arvense en les primeres etapes del cultiu. Tot i que l’eficàcia de la gestió mitjançant el NT-RC pot veure's fortament afectada per les variacions de les condicions de cultiu (incloent, però no limitades a les condicions meteorològiques interanuals, la temporalitat i l'eficàcia de les operacions agrícoles i les característiques agro-edafo-climàtiques de les finques), el seu ús pot contribuir a reduir la dependència de la pertorbació del sòl per a la gestió de flora arvense en sistemes hortícoles ecològics.
3. La importància relativa de la biomassa seca total, ja sigui dipositada sobre la superfície del sòl o incorporada al sòl com a adob verd, sobre la reducció de la densitat i la riquesa de la flora arvense i la composició de la comunitat arvense és menys important que la gestió de l’ASC i les condicions ambientals de l’any.
4. L’estratègia seleccionada per gestionar els ASC afecta l’energia total necessària i l’eficiència del sistema de cultiu. L’estratègia basada en el NT-RC comporta la reducció de l’ús de combustibles fòssil, la energia requerida per a la producció de maquinària i la mà d’obra, i augmenta l’energia que potencialment es pot reciclar dins del sistema de cultiu. No obstant això, NT-RC redueix significativament l’eficiència i la qualitat de la producció del cultiu comercial. Tot i això, hi ha una gran variabilitat en els paràmetres de rendiment energètic

que depenen de la maquinària emprada, de les condicions agronòmiques específiques, de les espècies ASC i del cultiu hortícola.

5. La incorporació dels indicadors energètics com el rendiment del cultiu (MCY) i l'energia potencialment reciclable (PRE) permeten avaluar la sostenibilitat dels sistemes tenint en compte els aspectes agronòmics i ambientals. El concepte de PRE permet posar èmfasi en la importància de reciclar la producció no comercialitzable dels cultius per augmentar el potencial de reciclatge del sistema.
6. La tesi doctoral posa de manifest la necessitat d'avaluar simultàniament diferents aspectes agronòmics, ambientals i ecològics com a mitjà per proporcionar una visió global de les conseqüències dels canvis que la gestió del ASC comporten sobre funcionament dels agroecosistemes. L'anàlisi multidimensional permet posar de manifest que la introducció dels ASC combinada amb l'ús del NT-RC és una tècnica prometedora per millorar el rendiment agronòmic (per exemple, menys abundància d'espècies arvenses) i reduir l'impacte ambiental (per exemple, augmentar l'energia que pot ser reciclada) i ecològic (per exemple, millorar la densitat d'activitat dels tàxons beneficiosos com ara com els caràbids i els estafilínids). No obstant això, el NT-RC disminueix el rendiment del cultiu i la seva qualitat, l'eficiència energètica de la producció i la densitat d'activitat de les aranyes.
7. La tesi doctoral també posa de manifest que encara es requereix més investigació per reduir la diferència de rendiment entre la gestió basada en l'ús del NT-RC i el T-GM mitjançant la millora de la fertilització durant el desenvolupament de cultiu comercial i programes específics de millora vegetal

adaptats a la nova tecnologia. A més, s'haurien d'incorporar estudis econòmics per conèixer fins a quin punt els costos associats a l'ús del NT-RC compensen la reducció del rendiment i la qualitat del cultiu comercial, tenim en compte els beneficis mediambientals.

8. Es necessita més investigació per identificar l'efecte de la presència de l'encoixinat creat per la gestió NT-RC sobre les condicions ambientals de la superfície del sòl, en diferents sòls i condicions climàtiques a Europa, i com afecta la aparició de flora arvense al llarg del cicle de cultiu comercial.
9. Des del perspectiva de disseminació dels resultats de la tesi doctoral al sector productiu, cal assenyalar la necessitat d'estudis a llarg termini que analitzin l'efecte del NT-RC sobre el funcionament dels sistemes hortícoles abans de suggerir als agricultors el seu ús de manera continuada.

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Apèndix 1. 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).

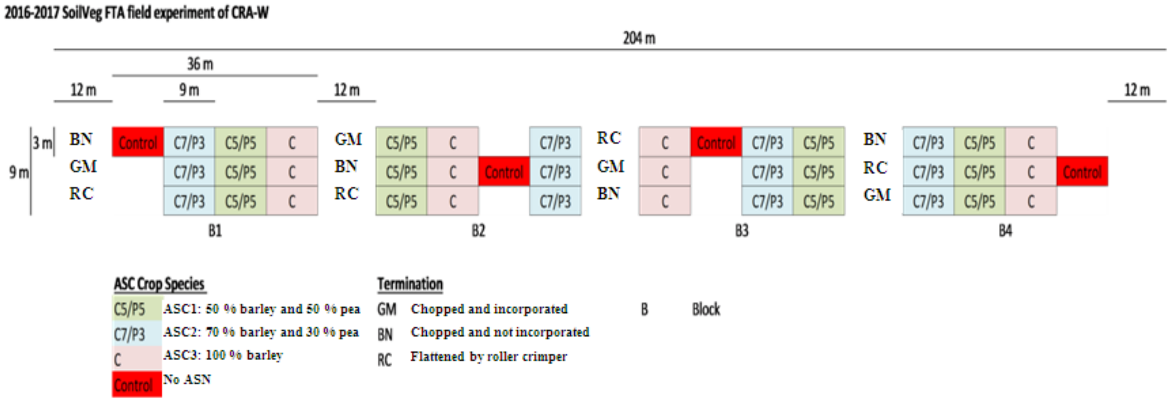
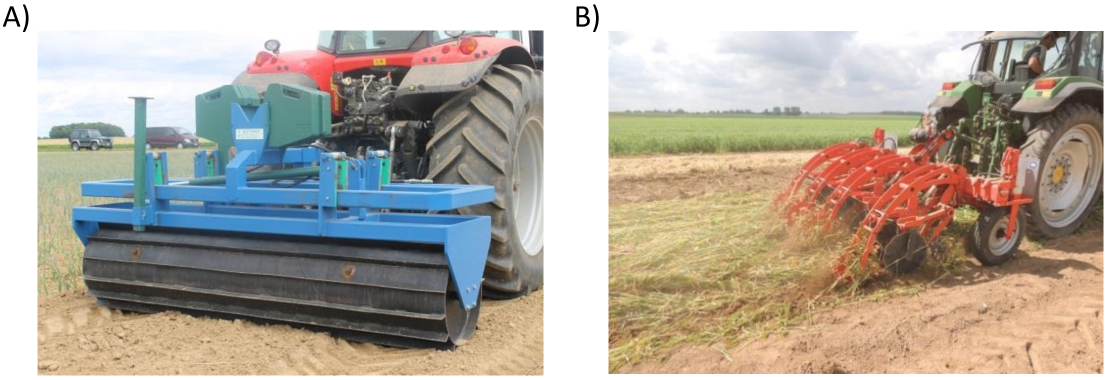


Figure 1. Experimental design of Walloon Agricultural Research Center (BE-CRA-W) trial. ASC composition: C5/P5 (green)- 50 % barley (*Hordeum vulgare* L.) + 50 % pea (*Pisum sativum* L.); C7/P3 (blue)- 70 % barley (*H. vulgare*) + 30 % pea (*P. sativum*); C (pink) – 100 % barley (H. *vulgare*); and Control (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).



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

Agronomic management

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

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

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

More information about this trial can be found in Arlotti, Lakkenborg Kristensen, Canali, De Neve, Huyghebaert, et al*.* (2019), Arlotti, Lakkenborg Kristensen, Canali, De Neve, Sans Serra, 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).

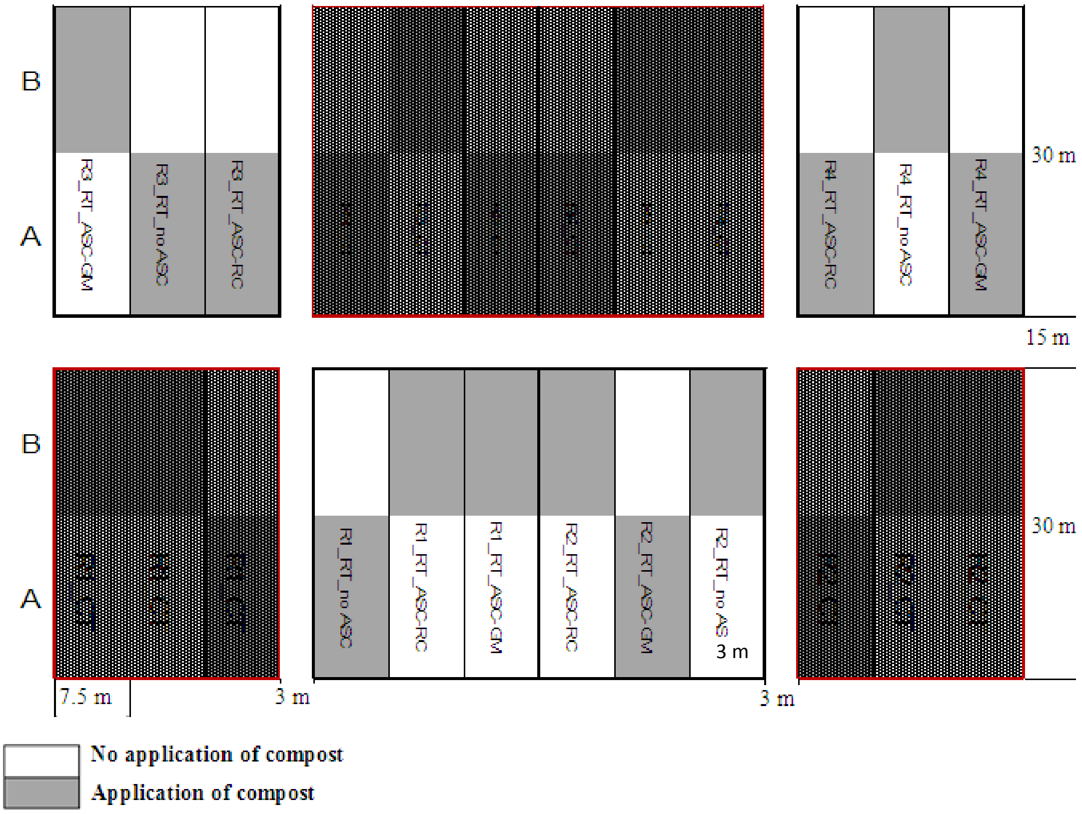


Figure 2 Experimental design of the Research Institute for Agriculture, Fisheries and Food (BE-ILVO) trial. Termination: R_RT_ASC-GM = ASC chopped and incorporated into the soil (T-GM); R_RT_ASC-RC = ASC flattened by a roller crimper (NT-RC); and R_RT_noASC = Control treatment without ASC. Compost factor: White - No application of compost; Grey - Application of compost.

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

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

Agronomic management

The ASC was sown on the 5th October 2015, and the 24th November 2016. In T-GM plots, the ASC was terminated by flail mowing on the 20th April 2016 and the 7th May 2017, and by superficial tillage on the 4th May 2016 and the 8th May 2017. The NT-RC plots were terminated on the 26th May 2016 and the 16th June 2017. The cash crop was transplanted and fertilised using a planting machine on the 27th May 2016, and the 21st June 2017 (Picture 4). Mechanical weeding was carried out on the 6th June, 6th, 26th, and 27th July 2016, and on the 13th, 17th, and 27th July 2017. Manual weeding was carried out during the periods: 6th to 22nd July, 28th July to 4th August, and 5th to 14th September 2016, and on the 14th, 27th, and 28th July 2017. Cash crop irrigation was only required during the second year and was conducted manually twice during the crop cycle. The cash crop harvest was performed on the 3rd and 4th November 2016, and the 7th November 2017.

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

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

Belgium - INAGRO (BE-INAGRO)

Field experiment type A

Experimental design

The field trial was newly established at the INAGRO organic farm station in Roeselare, Belgium (BE-INAGRO) (50° 90' 68" N and 3° 12' 72" 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 11.0 °C and 860 mm, and 11.3 °C and 697 mm, respectively. The trial soil had a sandy loamy texture and a 1.12 % organic carbon content.

The experiment was not repeated on the same plots in both years, and was moved to an adjacent area for the 2016–2017 cycle. The INAGRO trial farm has been managed according to organic farming regulations since 2003 and has a rotation over six years (grass-clover, leek, carrot/celeriac, cereals, cabbage, and potato). The trial design was a split plot with four replications. The experimental design was modified each year (Figures 3 and 4).

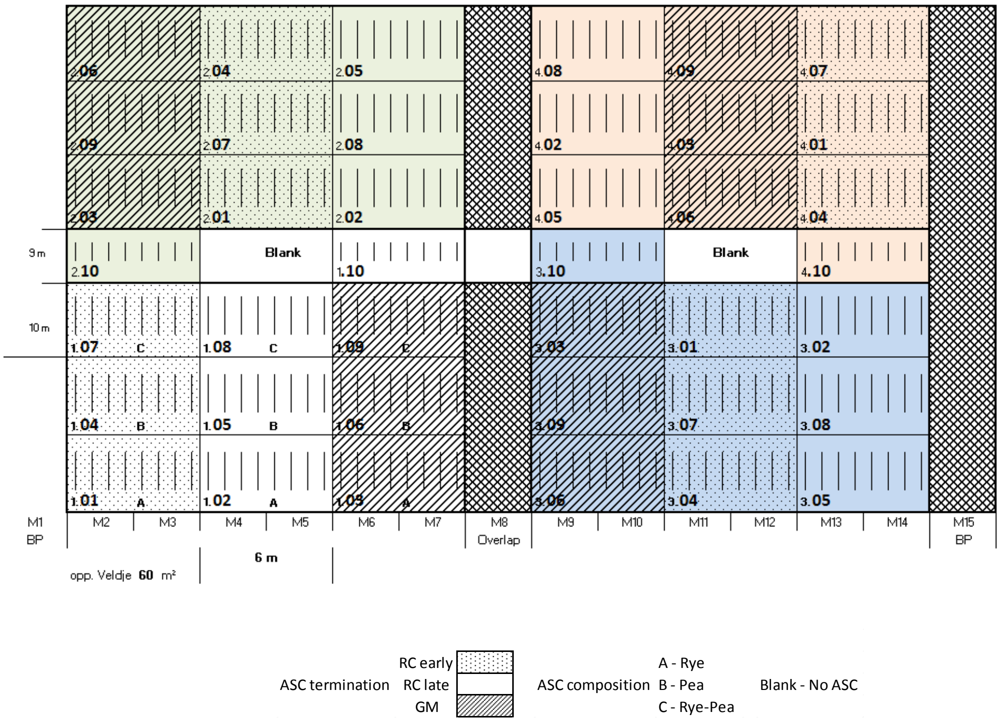


Figure 3. Experimental design at the INAGRO (BE-INAGRO) organic farm station during the first year. Termination: RC early - Roller crimper early termination; RC late - Roller crimper late termination; and GM - Mill cutting and non-inversion tillage (T-GM). ASC composition: A - winter rye (*Secale cereale* (L.) M. Bieb.), B - pea (*Pisum sativum* L.); C - rye-pea mixture; and Blank - No ASC.

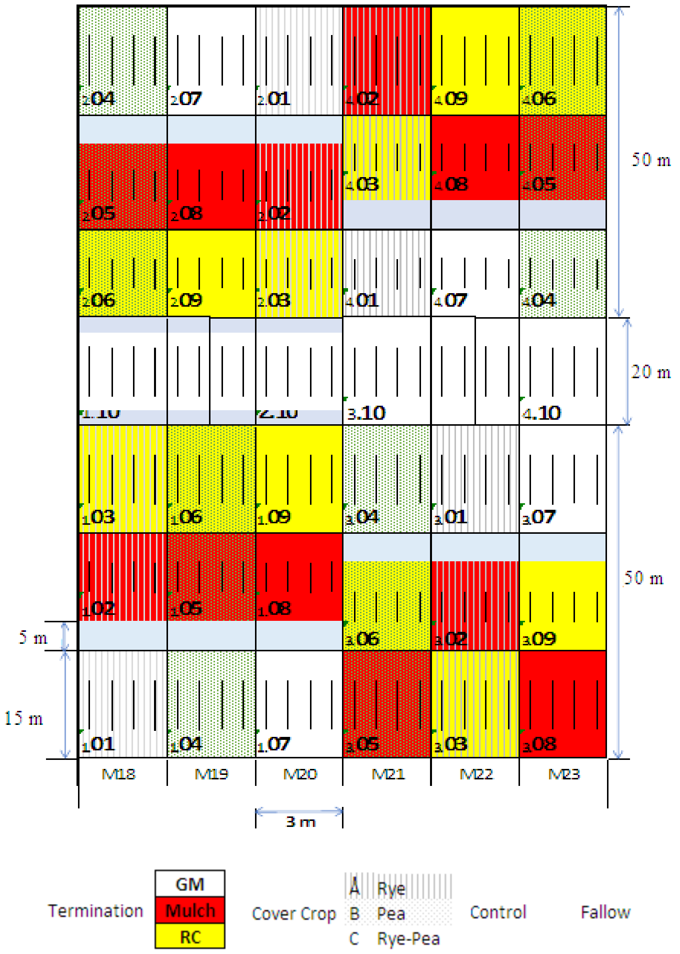
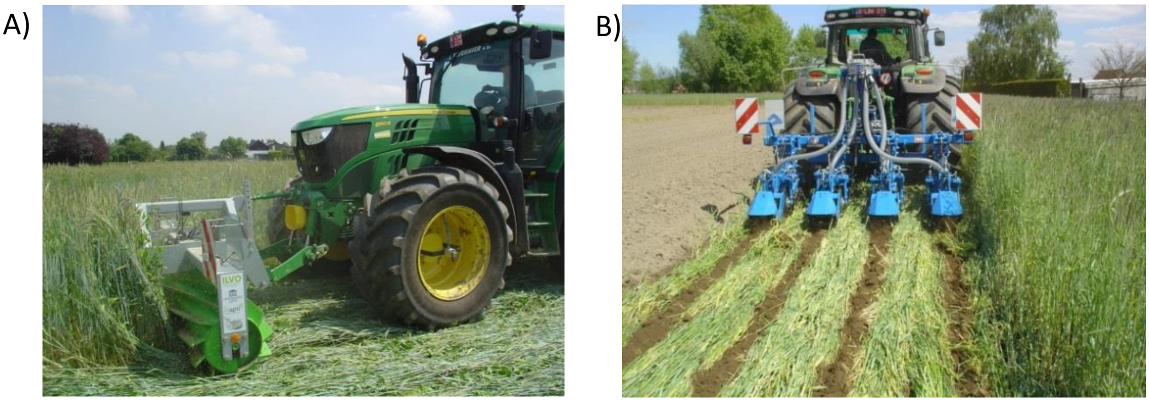


Figure 4. Experimental design at the INAGRO (BE-INAGRO) organic farm station during the second year. Termination: GM (white) - Incorporation by mill cutting one month before planting (T-GM); Mulch (red) - Mulching by flail mowing at planting (not-incorporated); and RC (yellow) - Roller crimper (NT-RC).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

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



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

Agronomic management

The trial was fertilised with composted farm yard manure (10 ton ha^{-1}) on October 12th, 2015, and with commercial organic fertiliser (Organic plant feed (OPF) granulate 11-0-5, Plant Health Cure B.V., Nederland) on March 16th, 2017. The ASC was sown on October 13th, 2015 and October 28th, 2016. During the first year, the ASC was terminated with the T-GM strategy on April 28th, 2016 and with the NT-RC strategy on

May 23rd, 2016. During the second year, termination happened on April 18th, 2017 in the T-GM plots, and on May 24th, 2017 in the NT-RC plots.

White cabbage was transplanted, with a row spacing of 0.70 m and a plant spacing of 0.30 m, using a planting machine on May 25th, 2016 and on May 30th, 2017 (Picture 6). The cabbages were fertilised with 50 kg N ha^{-1} commercial organic fertiliser (OPF granulate 11-0-5) on July 8th, 2016, during the first cycle, and on May 31st, 2017 during the second cycle. The cash crop was irrigated on August 24th, and 31st, 2016, and only once at the time of cash crop transplantation in 2017. In NT-RC plots, weeding operations were not required during the cash crop cycle. In T-GM plots, in the first year, weeding operations during the cash crop cycle were carried out by hoeing (June 8th, 2016) harrowing (June 9th, 2016) and manually (July 20th, and 22nd, 2016). In the second year, T-GM plots were weeded by mechanical weed control (June 15th, 2017) and manually (June 15th, and July 6th, 2017). The cash crop harvest was performed on November 21st, 2016 and November 7th, 2017. More information about this trial can be found in Hefner, Canali, et al. (2020).

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

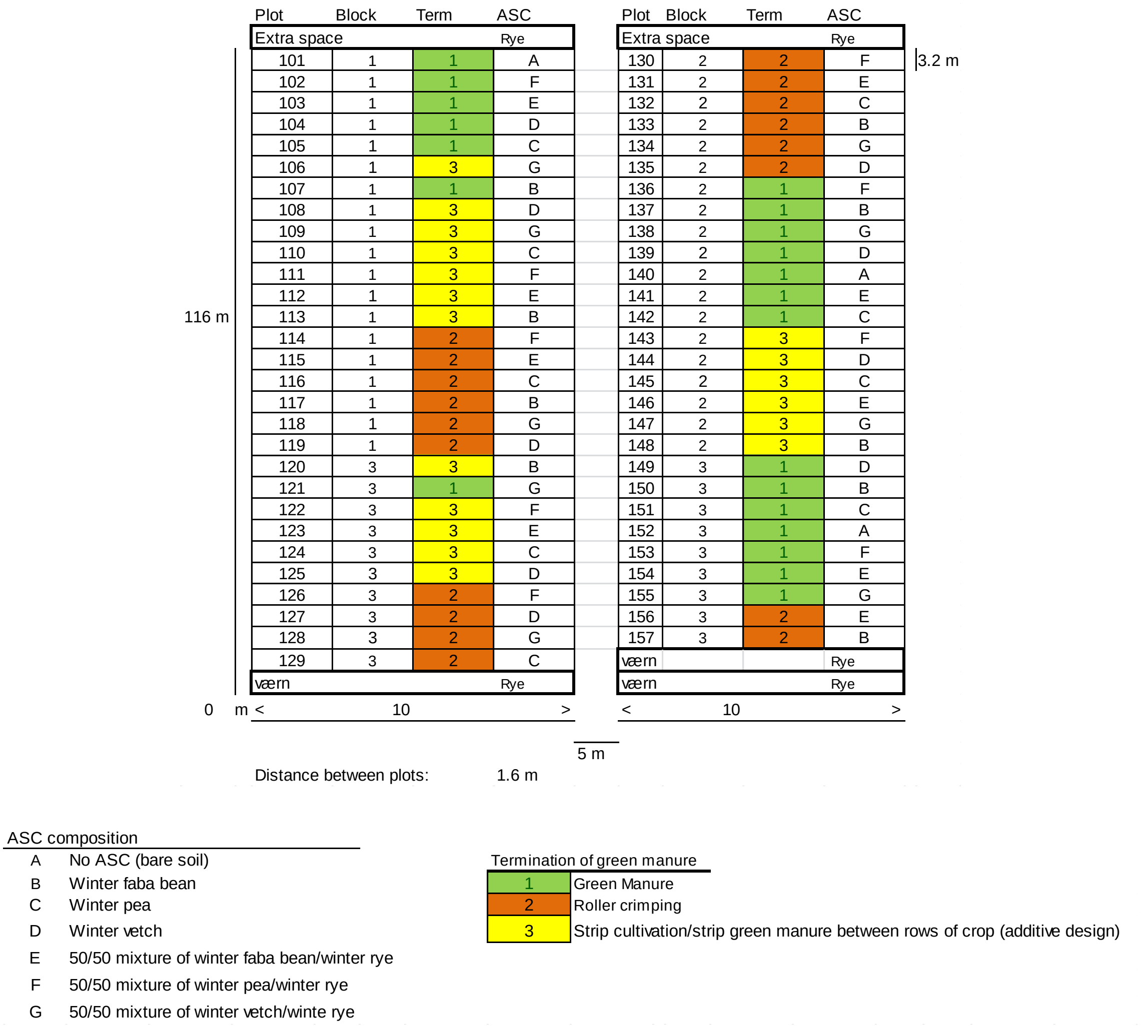
Denmark (DK)

Field experiment type A

Experimental design

The field trial was newly established at the Department of Food Science research centre of Aarhus University, located in Årslev, Denmark (55º 18′ N and 10º 27′ E), in the Atlantic North European climatic zone. The mean annual temperature was 9.3 °C and the mean annual rainfall, 614 mm during the first cycle (2015–2016), and 9.1 °C and 673 mm during the second cycle (2016–2017), respectively. The soil had a sandy loamy texture and a 1 % organic carbon content.

The experiment was not repeated on the same plots in both years, and was moved to an adjacent area for the 2016–2017 cycle. The two locations had been managed according to Danish organic farming regulations since 1996 and 2014, respectively. The previous crop grown in the area was barley (*Hordeum vulgare* L.). The trial had a split-plot randomised complete block experimental design with three replications, where ASC management was the whole-plot factor and ASC composition, the subplot factor. The experimental design was modified each year (Figures 5 and 6).



Plot	Block	Term	ASC
Extra space			Rye
101	1	1	A
102	1	1	F
103	1	1	E
104	1	1	D
105	1	1	C
106	1	3	G
107	1	1	B
108	1	3	D
109	1	3	G
110	1	3	C
111	1	3	F
112	1	3	E
113	1	3	B
114	1	2	F
115	1	2	E
116	1	2	C
117	1	2	B
118	1	2	G
119	1	2	D
120	3	3	B
121	3	1	G
122	3	3	F
123	3	3	E
124	3	3	C
125	3	3	D
126	3	2	F
127	3	2	D
128	3	2	G
129	3	2	C
værn			Rye

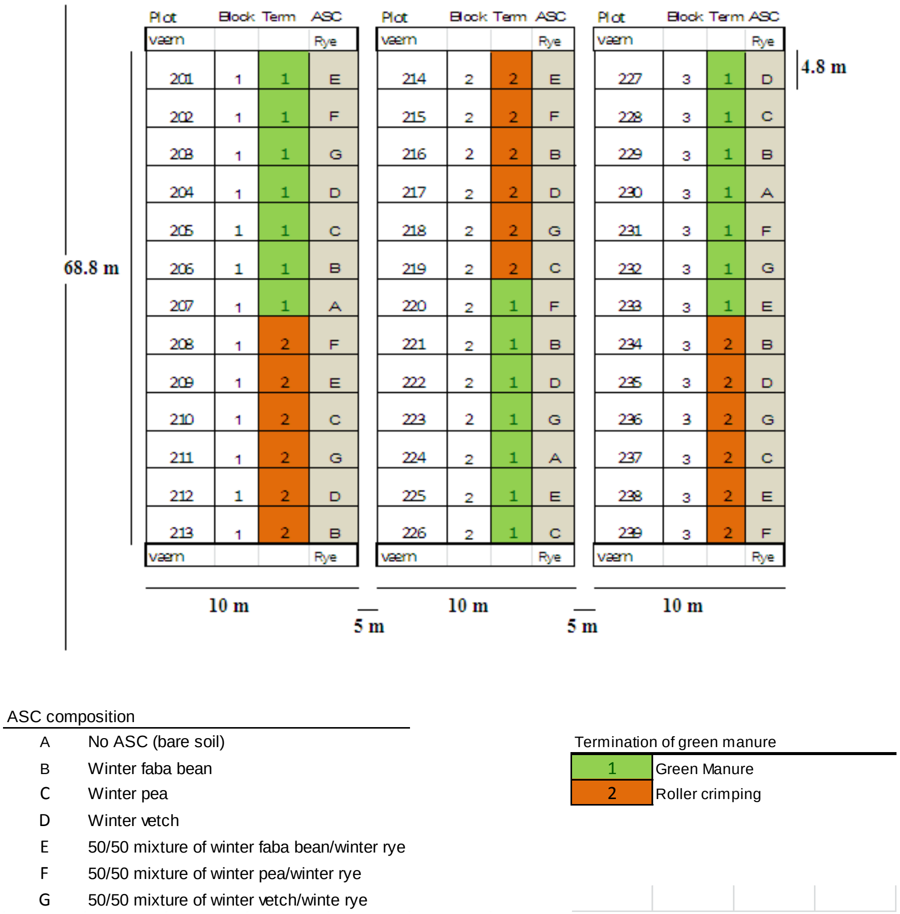
Plot	Block	Term	ASC
Extra space			Rye
130	2	2	F
131	2	2	E
132	2	2	C
133	2	2	B
134	2	2	G
135	2	2	D
136	2	1	F
137	2	1	B
138	2	1	G
139	2	1	D
140	2	1	A
141	2	1	E
142	2	1	C
143	2	3	F
144	2	3	D
145	2	3	C
146	2	3	E
147	2	3	G
148	2	3	B
149	3	1	D
150	3	1	B
151	3	1	C
152	3	1	A
153	3	1	F
154	3	1	E
155	3	1	G
156	3	2	E
157	3	2	B
værn			Rye
værn			Rye

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
G	50/50 mixture of winter vetch/winte rye

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

Figure 5. Experimental design of the organic farm station of the Department of Food Science research center of Aarhus University (DK) during the first cycle (2015–2016). 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); and 3 (yellow) - Strip cultivation/strip green manure between rows of crop. 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.



Plot	Block	Term	ASC
værn			Rye
201	1	1	E
202	1	1	F
203	1	1	G
204	1	1	D
205	1	1	C
206	1	1	B
207	1	1	A
208	1	2	F
209	1	2	E
210	1	2	C
211	1	2	G
212	1	2	D
213	1	2	B
værn			Rye

Plot	Block	Term	ASC
værn			Rye
214	2	2	E
215	2	2	F
216	2	2	B
217	2	2	D
218	2	2	G
219	2	2	C
220	2	1	F
221	2	1	B
222	2	1	D
223	2	1	G
224	2	1	A
225	2	1	E
226	2	1	C
værn			Rye

Plot	Block	Term	ASC
værn			Rye
227	3	1	D
228	3	1	C
229	3	1	B
230	3	1	A
231	3	1	F
232	3	1	G
233	3	1	E
234	3	2	B
235	3	2	D
236	3	2	G
237	3	2	C
238	3	2	E
239	3	2	F
værn			Rye

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
G	50/50 mixture of winter vetch/winte rye

Termination of green manure	
🟩 1	Green Manure
🟧 2	Roller crimping

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* L.), D: winter vetch (*Vicia sativa* L.), E: 50/50 mixture of winter rye (*Secale cereale* (L.) M. Bieb.) 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 (Picture 8). A control treatment of winter fallow (bare soil) was also included. Plot size was 3.2 × 10 m during the first year and 4.8 × 10 m during the second year. The cash crop was white cabbage (*Brassica oleracea* var. *capitata*).

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

Agronomic management

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}) on September 9th, 2015 and September 28th, 2016. The ASCs were sown on October 5th, 2015 and October 9th, 2016 and terminated on June 10th, 2016 and May 30th, 2017 (Picture 8).

Picture 8. View of Denamrk (DK) field trial before ASC termination.

White cabbage was transplanted using a three-row planting machine on July 1st, 2016, and on June 21st, 2017, with a row spacing of 0.5 m and a plant spacing of 0.5 m. Weed management was carried out in T-GM plots using a weed-brush machine in inter-rows on July 27th–29th and August 19th, 2016, and July 17th–19th, 2017, and manually with a hoe in inter-rows and intra-rows on September 26th–30th, 2016 and August 10th–22nd, 2017. In NT-RC plots, weeding operations consisted of the manual removal of above ground biomass of large weeds. During the first year, cabbages were fertilised with 50 kg N ha^{-1} feather meal pellets on August 25th, 2016. During the second year, cash crop fertilisation with 100 kg N ha^{-1} feather meal pellets was carried out a week before cabbage transplantation. Thirty kg N ha^{-1} lupine seeds (N-P-K: 4.5-0.4-0.9) were applied on June 15th, 2017, and 80 kg N ha^{-1} feather meal pellets on August 24th, 2017. Cash crop irrigation was only required during the first year and was conducted twice (in August and September) with sprinklers. The cabbage crop was harvested on November 11th, 2016, and November 2nd, 2017.

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

Estonia (EE)

Field experiment type A

Experimental design

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

The experiment was not repeated in the same plots in both years, and was moved to an adjacent area for the 2016–2017 cycle. The trial was established in an area certified organic from 2005. The previous crop grown in the area was red clover (*Trifolium pratense* L.). The trial had a strip-plot design with ASC strips and ASC management strategies crossed with a fertiliser factor, and three replicates per treatment (Figure 7).

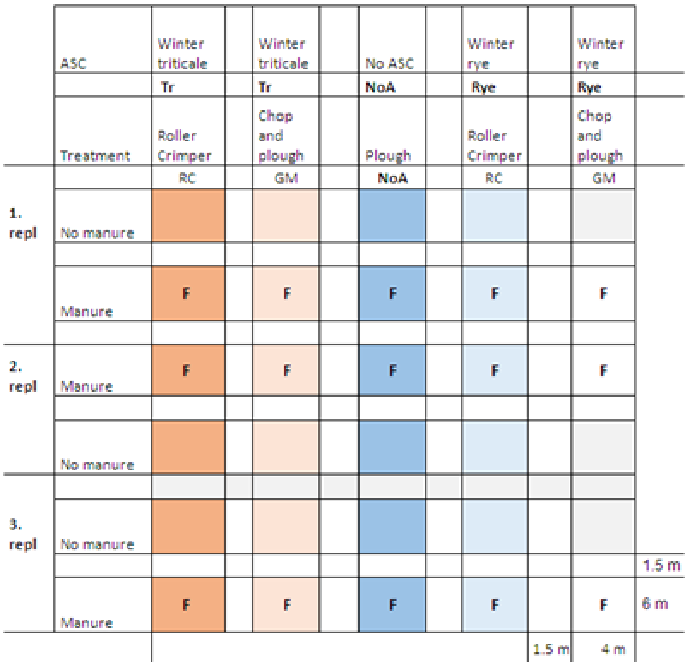


Figure 7. Experimental design of the research field at the organic farm station at Jõgeva in eastern Estonia (EE). Termination: RC - Roller-crimped (NT-RC); and GM - Chopped by a flail mower, then ploughed and levelled by a cultivator (T-GM). ASC composition: ASC1 - 100 % Winter rye; and ASC2 - 100 %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

The two ASC termination strategies were: (1) roller-crimped (NT-RC), and (2) chopped by a flail mower, then ploughed, and levelled by a cultivator (T-GM). The roller crimper was 2 m wide and weighed 800 kg during the first year ASC termination, and 1,200 kg during the second, and was designed and constructed by Soldo Macchine Agricole (Grassano, Italy) (Picture 9). In the NT-RC plots, furrows for cash crop transplanting were created by in-line tillage (Picture 9). The ASC species composition was: ASC1 - 100 % winter rye (*Secale cereale* (L.) M. Bieb.) (180 kg ha^{-1}), and ASC2 - 100 % winter triticale (× *Triticosecale blaringhemii* A. Camus) (155 kg ha^{-1}). The fertilisation factor consisted of: (1) application of 30 t ha^{-1} solid 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 6 × 4 m. The cash crop was white cabbage (*Brassica oleracea* var. *capitata*).

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.

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

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

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

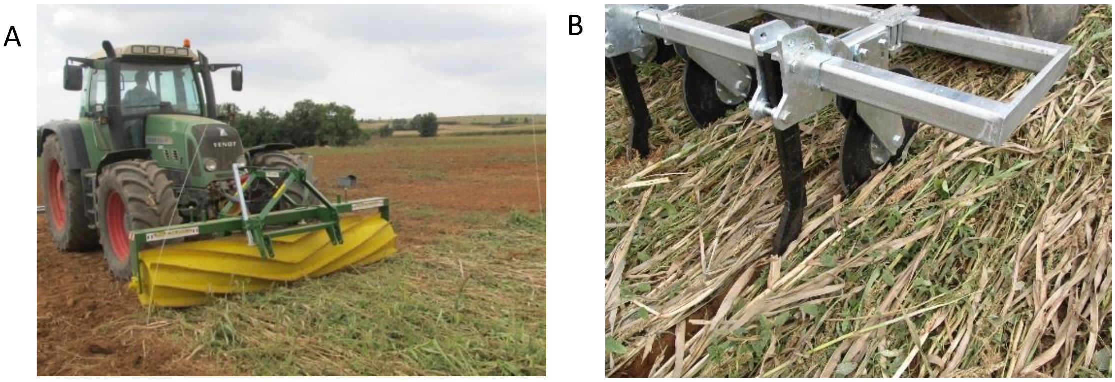
Spain (ES)

Experimental design

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

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

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



Picture 11. Machinery used for NT-RC management in the Gallecs Area of Natural Interest, Barcelona, Spain (ES). A - Roller crimper. B - In-line tiller.

Field experiment type A

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

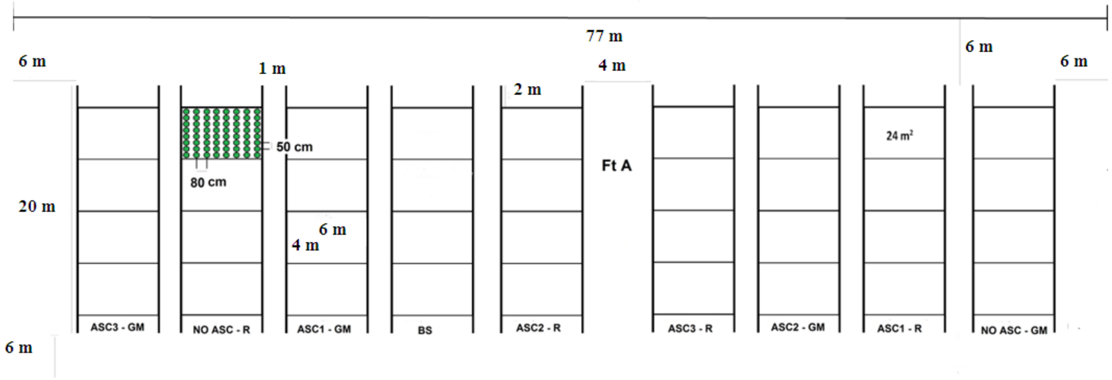


Figure 8. Experimental design of field experiment type A established in the Gallecs Area of Natural Interest, Barcelona, Spain (ES). Termination: ASC-R - Flattened by roller crimper (NT-RC); and ASC-GM - mowed, chopped and incorporated into the soil as green manure using a chisel plough (T-GM). ASC composition: ASC1 – 100 % cereal mixture (81 % *Avena byzantina* K. Koch and 19 % *Hordeum vulgare* L.); ASC2 - 70 % cereal mixture + 30 % *Vicia sativa* L.; and ASC3 - 50 % cereal mixture + 50 % *V. sativa* L.; 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*).

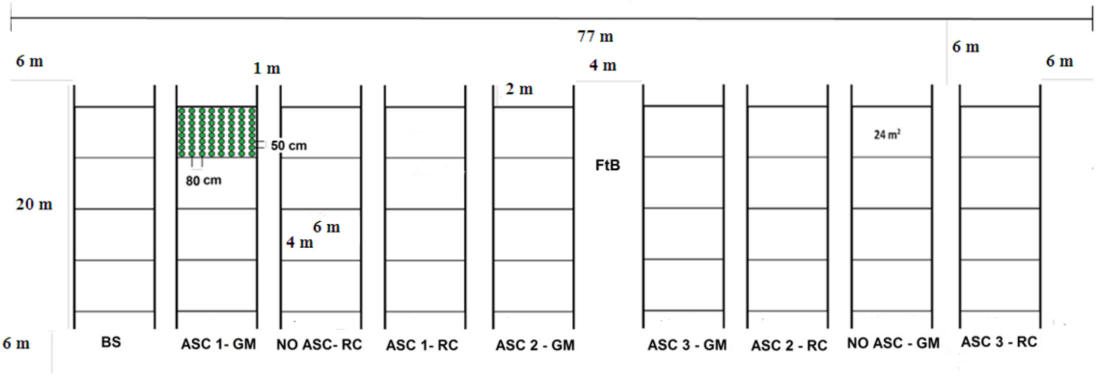


Figure 9. The experimental design of the FtB field experiment established in the Gallecs Area of Natural Interest, Barcelona, Spain (ES). Termination: ASC-R - Flattened by roller crimper (NT-RC); and ASC-GM - mowed, chopped and incorporated into the soil as green manure using a chisel plough (T-GM). ASC composition: ASC1 - 100 % Vigna unguiculata (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. BS - control treatment maintaining the soil without plant cover (bare soil).

Agronomic management

Field experiment type A

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

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

Picture 12. View of the FtA field experiment established in the Gallecs Area of Natural Interest, Barcelona, Spain (ES) during growth of the cash crop.

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).

More information about this trial can be found in Navarro-Miró *et al.* (2017), Navarro-Miró, Iocola, et al. (2019), and Navarro-Miró, Blanco-Moreno, et al. (2019).

France (FR)

Field experiment type A

Experimental design

The field experiment was newly established at the experimental organic research centre of the Groupe de Recherche en Agriculture Biologique (GRAB) in Avignon, southern France (FR) (43° 54' 23.8" N and 4° 53' 06.4" E). This location represented the Mediterranean North European climatic zone. During the first cycle (2015–2016), the mean annual temperature was 15.5 °C and the mean annual rainfall, 521 mm, and in the second cycle (2016–2017) these environmental factors were 15.3 °C and 558 mm, respectively. The trial soil had a clay loam texture and a 1.86 % organic carbon content. The experiment was repeated on the same plots in both years, but with some changes in the second year. The selected experimental field had been under organic farming management from 2000. The previous crops grown were diversified varieties of squash (*Cucurbita* sp.). The trial had a randomised strip-plot experimental design with three replicates during the first year and four during the second year, where ASC management strategy (i.e., NT-RC or T-GM) was the strip factor, and the ASC composition was the subplot factor (i.e., six different ASC compositions). The experimental design was modified each year (Figures 10 and 11).

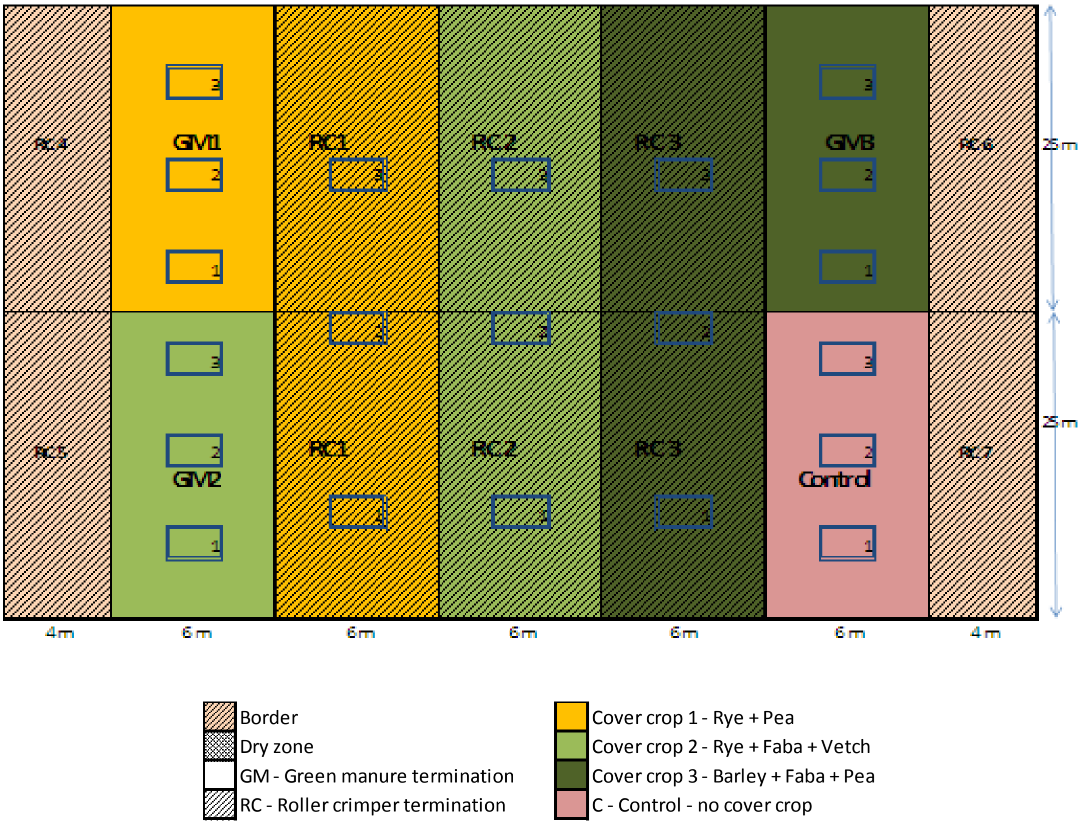


Figure 10. First cycle (2015–2016) experimental design of the trial established at the experimental organic research centre of the Groupe de Recherche en Agriculture Biologique (GRAB) in Avignon (FR). Termination: RC - Cover crop flattened by a roller crimper + in-line tillage to create the transplanting 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* (L.) M. Bieb. + 50 % *Pisum sativum* L.; ASC2 - 30 % *S. cereale* + 40 % *Vicia faba* L. + 40 % *Vicia villosa* Roth; ASC3 - 50 % *Hordeum vulgare* L. + 37 % *V. faba* + 40 % *P. sativum*; and Control - Control treatment maintaining the soil without plant cover (bare soil).

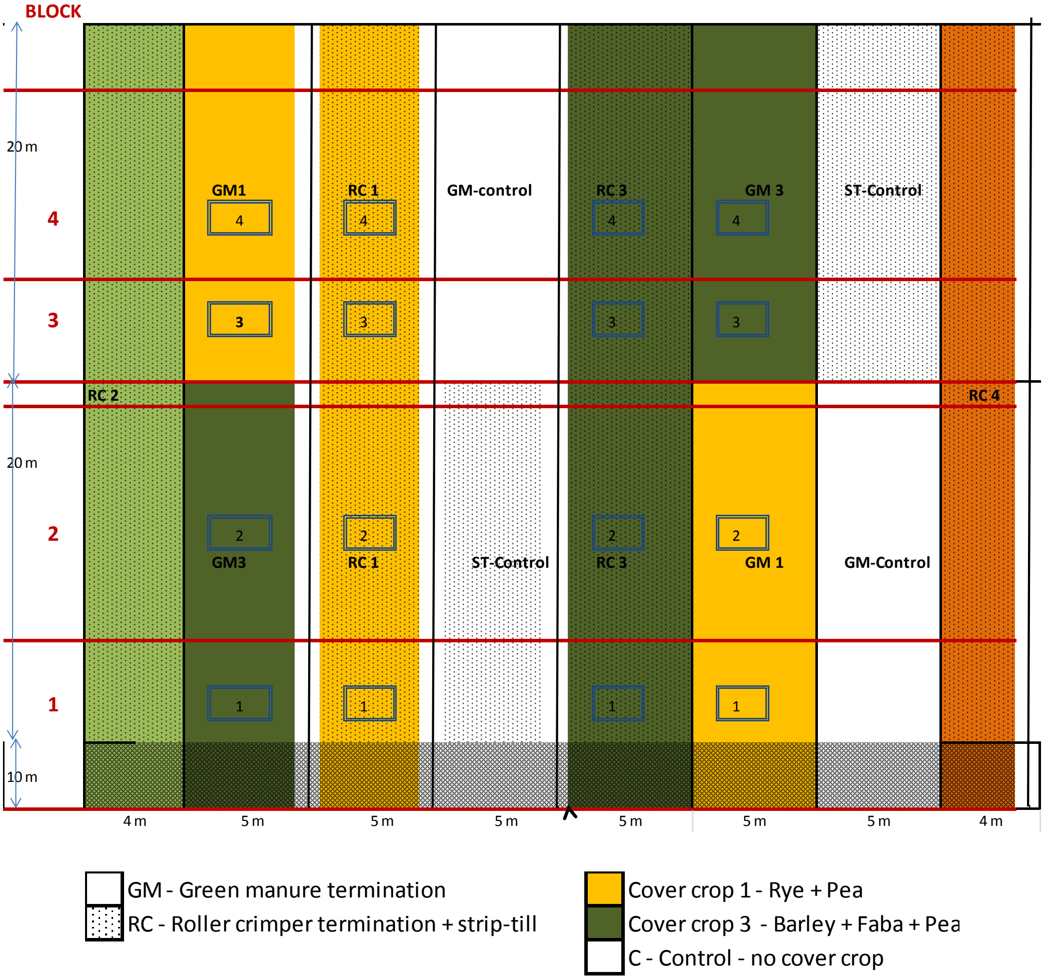


Figure 3. Second cycle (2016–2017) experimental design of the trial established at the experimental organic research centre of the Groupe de Recherche en Agriculture Biologique (GRAB) in Avignon (FR). Termination: RC - Cover crop flattened by a roller crimper + in-line tillage to create the transplanting 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* (L.) M. Bieb. + 50 % *Pisum sativum* L.; and ASC3 - 50 % *Hordeum vulgare* L. + 37 % *Vicia faba* L.+ 40 % *P. sativum*. L. 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 first year, the ASC species composition was: ASC1: 50 % *Secale cereale* (L.) M. Bieb. (60 kg ha^{-1}) + 50 % *Pisum sativum* L. (80 kg ha^{-1}), ASC2: 30 % *S. cereale* (40 kg ha^{-1}) + 40 % *Vicia faba* L. (80 kg ha^{-1}) + 40 % *Vicia villosa* Roth (20 kg ha^{-1}), and ASC3: 50 % *Hordeum vulgare* L. (50 kg ha^{-1}) + 37 % *V. faba* (73 kg ha^{-1}) + 40 % *P. sativum* (67 kg ha^{-1}). In the second year, only two of the previous ASC compositions were sown: ASC1 - 50 % *S. cereale* (60 kg ha^{-1}) + 50 % *P. sativum* (80 kg ha^{-1}), and ASC3 - 50 % *H. vulgare* (50 kg ha^{-1}) + 37 % *V. faba* (73 kg ha^{-1}) + 40 % *P. sativum* (67 kg ha^{-1}). Plot size was 10 × 6 m during the first year and 10 × 5 m during the second year. The cash crop was butternut squash (*Cucurbita moschata* Duchesne cv. 'Ariel').

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

Agronomic management

The trial was fertilised with 2 t ha^{-1} of organic commercial fertiliser (AB'Flor, N-P-K: 6-7-10) and 6 t ha^{-1} of compost (with approximately 65 % green waste and 35 % horse manure). ASCs were sown on October 1st, 2015 and October 11th, 2016. ASCs were terminated on April 26th, 2016 in the T-GM plots and April 28th, 2016 in the NT-RC plots, and on April 18th, 2017 in the T-GM plots, and on April 19th, 2017 in the RC3 plots and May 16th, 2017 in the RC1 plots.

The butternut squash were manually transplanted on June 9th, 2016 and June 8th, 2017, with a row spacing of 2 m and a 0.5 m plant spacing (Picture 15). The cash crop plants were fertilised with commercial organic fertiliser (Dix® 9.2.2+1 MgO Italpollina). In the first year, 80 kg ha^{-1} N was applied with the commercial organic fertiliser on June 6th, 2016. In the second year, 72 kg ha^{-1} N was applied with the commercial organic fertiliser on May 31st, 2017 (i.e., before soil tillage and cash crop transplantation) in the T-GM treatments, and localised in the strip-till lines on June 6th, 2017 in the NT-RC treatments. During both years, butternut squash was irrigated by drip irrigation according to crop needs.

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

In the first year, weeding operations were performed in the inter-rows of the T-GM1 and T-GM2 plots using a rototiller on June 22nd, 2016, and manual weeding was performed three times in all treatments on the 23rd of June, 12th of July and 9th of August, 2016. During the second year, manual weeding was performed twice in all treatments on the 23rd of June, and 5th of July 2017. The cash crop was manually harvested on September 7th, 2016, and September 11th, 2017.

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

Italy (IT)

Both parallel field experiments Type A (FtA) and Type B (FtB) were newly established at the Experimental Farm of Metaponto belonging to the Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA) in southern Italy (IT) (40º 24′ N and 16° 48′ E). This location represented the Mediterranean North European climatic zone. In FtA, during the first cycle (2015–2016), the mean annual temperature was 16.7 °C and the mean annual rainfall, 539 mm, and during the second cycle (2016–2017) these environmental factors were 16.5 °C and 402 mm, respectively. In FtB, during the first cycle (2014–2015) the mean annual temperature was 16.6 °C and the mean annual rainfall, 470 mm, and during the second cycle (2015–2016), these environmental factors were 16.7 °C, and 539 mm, respectively. The trial soil had a clay texture and contained on average 1.1 % organic carbon content.

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

Picture 16. Machinery used for NT-RC management 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). A tractor equipped with a roller crimper and in-line tiller.

Experimental design

Field experiment type A

The previous crop grown in the area was fennel (*Foeniculum vulgare* Mill.). The experimental layout consisted of a split-split-plot with main plots arranged as a randomised complete block design, with three factors and three replications. The main plot was the ASC factor, and the subplot was assigned to the ASC management strategy, and the split-plot to the fertilisation factor (Figure 12).

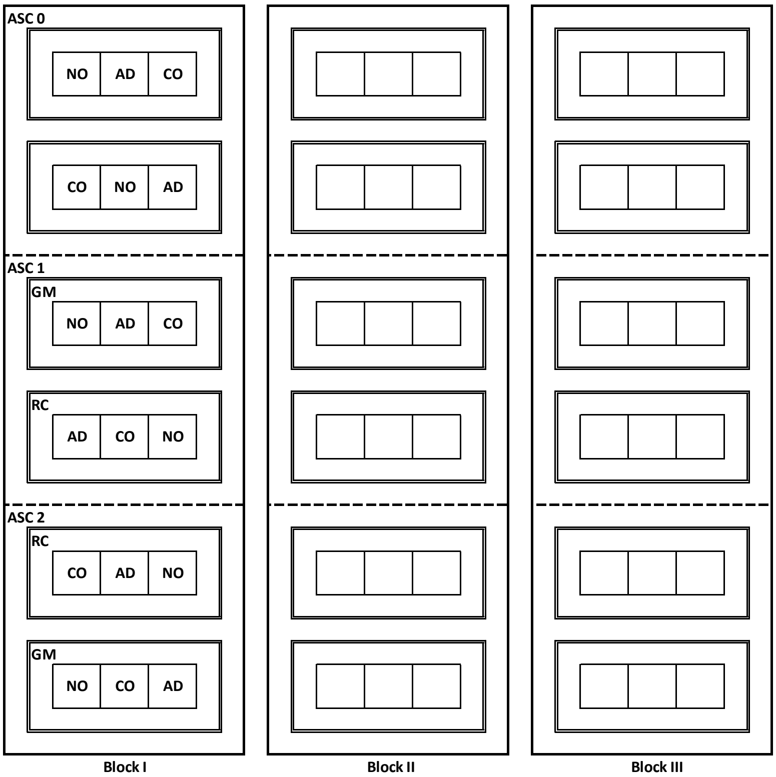


Figure 12. The FtA experimental design at the Experimental Farm of Metaponto belonging to the Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA) in southern Italy (IT). Termination: RC - Roller crimper + in-line tillage to create the transplanting furrows (NT-RC); and GM - 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 L. + 80 % *Vicia sativa* L.; and ASC2 - 20% H. vulgare + 80 % *Vicia faba* L. var. *minor*. Fertilisation factor: NO - no fertiliser; CO - Commercial organic mineral fertiliser allowed in organic farming; and AD - Anaerobic digestate from cattle residues.

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

Field experiment type B

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

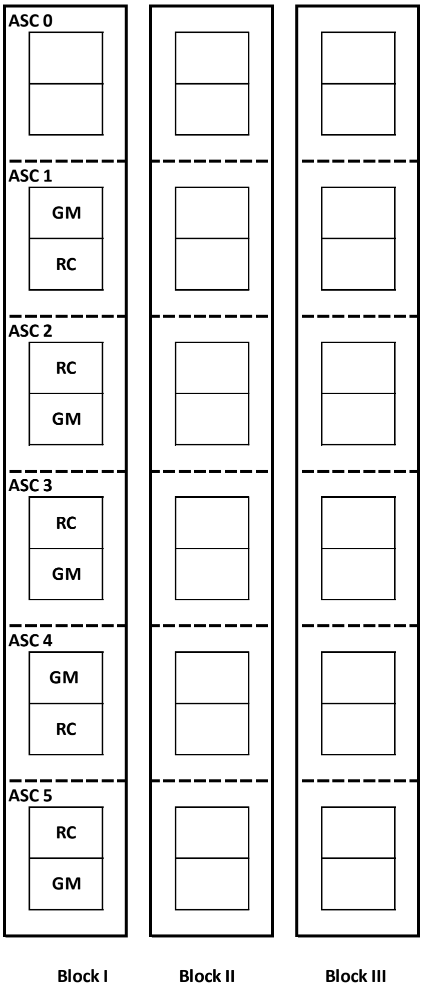


Figure 13. The FtB experimental design at the Experimental Farm of Metaponto belonging to the Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA) in southern Italy (IT). Termination: RC - Roller crimper + in-line tillage to create the transplanting furrows (NT-RC); and GM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

In 2015, ASC compositions were: ASC1 - 100 % cowpea (*Vigna unguiculata* (L.) Walp.), ASC2 - 70 % cowpea + 30 % pearl millet (*Pennisetum glaucum* (L.) R. Br.), ASC3 - 50 % cowpea + 50 % pearl millet, and ASC4 - 40 % cowpea + 30 % pearl millet + 30 % radish

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

Agronomic management

Field experiment type A

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

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

Field experiment type B

ASCs were sown on April 21st, 2015 and April 19th, 2016, and were irrigated on emergence. Commercial organic fertiliser (150 kg ha^{-1} N, 450 kg ha^{-1} P_2O_5, and 150 kg ha^{-1} K_2O) was applied just before the ASC termination, whereas in the second year, fertiliser was applied during cash crop development. ASC management was carried out on July 29th, 2015, whereas in the second year, the ASC was terminated by T-GM on July 27th, 2016, and by NT-RC on July 28th, 2016.

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

More information about this trial can be found in Navarro-Miró et al. (2017), Navarro-Miró, Iocola, et al. (2019) and Navarro-Miró, Blanco-Moreno, et al. (2019).

Slovenia (SI)

Field experiment type A

Experimental design

The field trial was newly established at the University of Maribor (Pivola), Faculty of Agriculture and Life Sciences (UM), Slovenia (SI) (46° 30' N and 15° 37' E). This trial represented the Alpine South European climatic zone. During the first cycle (2015–2016), the mean annual temperature was 10.9 °C and the mean annual rainfall, 1,009 mm, and during the second cycle (2016–2017) these environmental factors were 11.1 °C and 961 mm, respectively. The trial soil had a loam texture with an average 2.66 % organic carbon content.

The experiment was not repeated in the same plots in both years, and was moved to an adjacent area for the 2016–2017 cycle. The previous crop grown in the area was barley. The trial had a split-split-plot design with plots arranged in a randomised complete block design, with three factors and four repetitions (Figure 14).

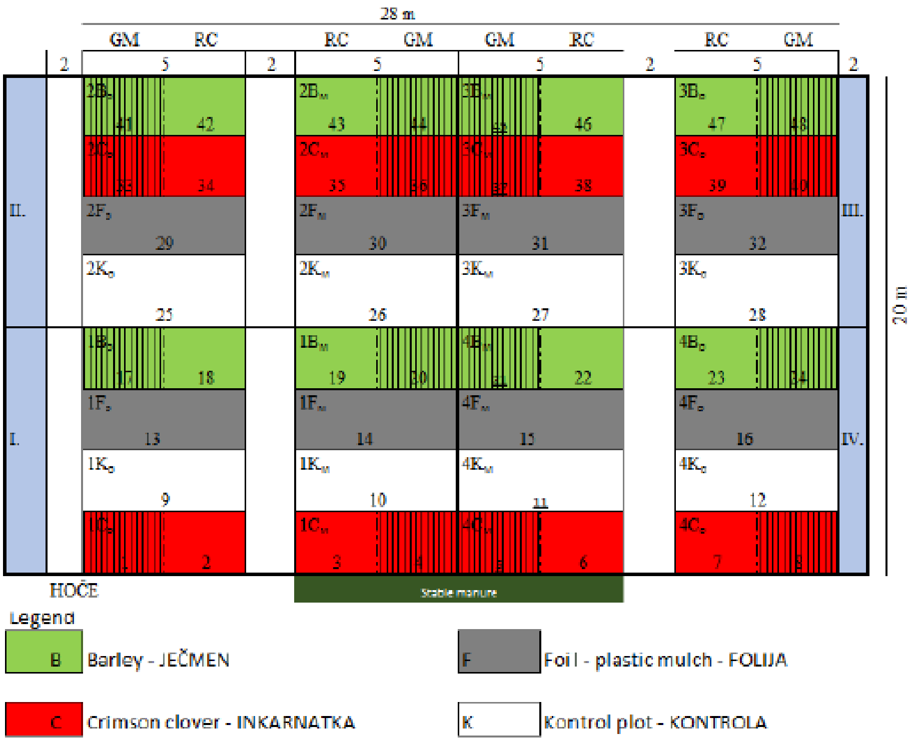


Figure 14. Experimental design of the trial established at the University of Maribor (Pivola), Faculty of Agriculture and Life Sciences (UM), Slovenia (SI). ASC compositions were: ASC1 (green) - 100 % *Hordeum vulgare* L.; and ASC2 (red) - 100 % *Trifolium incarnatum* L.; and two different controls: 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.

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

(30 t ha^{-1}) before sowing the ASCs, and O - no manure application. Plot size was 2.5 × 2.5 m. The cash crop was cauliflower (*Brassica oleracea* var. *botrytis* L.).

Picture 18 Machinery used for NT-RC management in the trial established at the University of Maribor (Pivola), Faculty of Agriculture and Life Sciences (UM), Slovenia (SI). A tractor equipped with a roller crimper and in-line tiller.

Agronomic management

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

The cauliflower crop was transplanted on June 3rd, 2016, and May 24th, 2017 with a row spacing of 0.6 m and a 0.40 m plant spacing (Picture 19). During the cash crop cycle, all plots were fertilised using commercial organic fertilisers when the cash crop was transplanted (70 kg ha^{-1} N), and during cash crop development (70 kg ha^{-1} N). During the second year, the cash crop was irrigated twice using micro-sprinklers. Weed management was performed manually in all treatments. During the first cycle, three weeding operations were carried out in the T-GM and control plots on June 29th, 2016, July 19th, 2016, and August 11th, 2016. In the NT-RC plots, only one operation was required (August 12th, 2016). During the second cycle, four weeding operations were carried out in the T-GM and control plots (June 19th, 2017, July 5th, 2017, July 26th, 2017, and August 17th, 2017), whereas in the NT-RC plots, two operations were required (July 5th, 2017 and August 9th, 2017). The cash crop harvest was performed on September 29th, 2016 and September 5th, 2017.

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

More information can be found in Bavec, Robačer, Bavec, et al. (2017), Bavec, Robačer, Lisec, et al. (2017) and Navarro-Miró, Blanco-Moreno, et al. (2019).

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Apèndix 2. Details of sampling procedures for Carabidae, Staphylinidae and Araneae, N leaching, beta-glucosidase, marketable yield and cash crop quality carried out in each trial.

2. Carabidae, Staphylinidae and Araneae trapping methodology

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

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

Field experiment type A

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

Denmark (DK)

Field experiment type A

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

Italy (IT)

Field experiment type A and type B

Each trap consisted of two collecting cups (600 mL; 10-cm diameter) connected by a 10-cm-high and 1-m-long Plexiglas barrier. Cups were filled with 40 % aqueous solution of propylene glycol as a killing and preservative agent.

In FtA, traps were active for seven out of 21 days from early June to late July in 2016 and 2017. Trapped arthropods were collected four times.

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

Slovenia (SI)

Field experiment type A

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

Spain (ES)

Field experiment type B

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

3. Beta-glucosidase

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

Belgium - INAGRO (BE-INAGRO)

Field experiment type A

The activity of β-glucosidase was assessed using the method described in Alef and Nannipieri, (1995). In short, 4 ml of modified universal buffer (pH 6.0) and 1 ml of 25 mM p-nitrophenyl-β-D-glucospyranoside solution was added to one gram of the pre-incubated moist soil. The soil suspensions were incubated for 1 h at 37 °C. After incubation, 1 ml of $CaCl_2$ and 4 ml of Tris buffer (pH 12.0) were added. If needed, soil suspensions were diluted twice with Tris buffer (pH 10.0) to make the filtrates fit the range of the p-nitrophenol standard series. The colour intensity of the filtrates and standard series was measured at 400 nm with a Cary 50 UV-Visible spectrophotometer (Varian Inc., Palo Alto, United States).

Denmark (DK)

Field experiment type A

Beta-glucosidase activity was measured by adding 1 ml of 25 mM p-nitrophenyl-β-D-glucoside solution and 4 ml of modified universal buffer to two technical replicates of 1 g of sieved soil (fresh weight). The samples were incubated at 37 °C for 1 h. P-nitrophenyl-β-D-glucoside solution was added to the control samples after incubation. Subsequently, 1 ml of 0.5 M $CaCl_2$ and 4 ml of Tris-buffer pH 12 were added to the samples, which were then filtered immediately using Whatman nº. 5 papers. Released p-nitrophenol in the extract was determined by measurement of the optical density with a Varian Cary 50 spectrophotometer at 400 nm. Beta-glucosidase activity was determined as the difference between experimental and control samples.

Italy (IT)

Field experiment type A

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

4. N leaching

The nitrogen leaching potential (N leaching) was measured using as an indicator the soil mineral nitrogen at harvest of the cash crop (Hutchings and Kristensen 1995).

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

Field experiment type A

The mineral nitrogen content was assessed using a soil depth of 0.3 m because the dry weather did not allow us to sample more deeply. Six samples were collected per plot area and mixed into one composite sample. Soil mineral nitrogen, measured when the cash crop was harvested, was extracted by 0.5 M KCl (1:5, w/v) and measured by continual flow colourimetry according to QuickChem® Method 12-107-06-3-B and QuickChem® Method 12-107-04-1-B for NH_4^+-N and NO_3^--N, respectively.

Belgium - INAGRO (BE-INAGRO)

Field experiment type A

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

Denmark (DK)

Field experiment type A

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

Estonia (EE)

Field experiment type A

For soil mineral nitrogen, measured when the cash crops were harvested, four subsamples were taken per plot and mixed into one composite sample. Soil N_{min} was determined by the extraction of nitrate and ammonium in 2-M KCl (1:10, w/v) for 1 h and by analysis of the supernatant using standard colourimetry. The analysis of the supernatant was performed twice to control for intra-laboratory variability.

Italy (IT)

Field experiment type A

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

5. Marketable yield

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

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

Field experiment type A

The cabbage marketable yield was estimated on two days (October 25th and 26th, 2017) by evaluating 21 cabbages per plot selected in the centre of the plot along three central lines. The marketable heads was assessed by measuring the dry matter (t ha^{-1}; 60 °C until constant weight). 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

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

Field experiment type B

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

6. Cash crop quality

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

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

Field experiment type A

To assess the marketable yield, the cash crop quality was estimated measuring the head diameter (mm) of 21 cabbages collected from the centre of the selected plot. The minimum head diameter considered as marketable was 130 mm.

Estonia (EE)

Field experiment type A

In both years, cabbage quality was assessed by measuring the head diameter of five randomly chosen plants per plot.

Spain (ES)

Field experiment type A

In the first year, we estimated the cash crop quality by measuring the length of each pepper when harvesting of eight random plants per plot in twelve weekly samplings. In the second year, we used the same procedure, except that we chose five plants at random per plot and five biweekly samplings.

Field experiment type B

In both years, cabbage quality was assessed by measuring the head diameter of five randomly chosen plants per plot.

France (FR)

Field experiment type A

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

Italy (IT)

Field experiment type A

At harvest, in both years, tomato quality was assessed by measuring the following parameters: mean fruit weight (g), total soluble solids (refractometric index, °Brix) and marketable fruit dry matter (t ha^{-1}; 70 °C until constant weight).

Field experiment type B

At harvest, in both years, cauliflower head quality was assessed by measuring the circumference and length (cm) of heads and the dry matter weight (t ha^{-1}; 70 °C until constant weight) of marketable heads.

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Apèndix 3. Minimum and maximum value of each variable in each trial

Maximum 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-GM) of agroecological service crop (ASC) management strategies. We combined results from 11 organic arable vegetable field trials located in Belgium (BE), Denmark (DK), Estonia (EE), France (FR), Italy (IT), Slovenia (SI), and Spain (ES). In BE, three different trials were set up across the country (BE-ILVO, BE INAGRO, and BE-CRA-W). Two parallel field experiment types were carried out: FtA - Spring-summer cash crop and FtB- Autumn-winter cash crop.

			Ecological indicators			Environmental indicators			Agronomic indicators			
Country	Trial	Termination	Carabidae AD	Staphylinidae AD	Araneae AD	PRE-EUE	N leaching	Beta-glucosidase	Weed density	Marketable yield	Cash crop quality	M-EUE
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			

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