**A multi-criteria evaluation of fall vegetation services and dis-services in 30 cropping systems varying in cover crop system, tillage and residue management**

**Virginia A. Nichols1 Marco Gentili1 Emma Randahl-Beltran1 Mette Sønderskov1 Bo Melander1**

1Department of Agroecology, Aarhus University, 1 Forsøgsvej, 4200 Slagelse, Denmark

Correspondence

Virginia A. Nichols

Email: [gina.nichols@agro.au.dk](mailto:gina.nichols@agro.au.dk)

Marco…

Emma

Mette

Bo…

Funding information

[List name of funders and grant details]

Bo?

Word count = 7000 maximum (including all tables, legends and references)

**Abstract (250 words max)**

With increasing environmental pressures from population growth and climate change, there is an increasing need to holistically evaluate the roles of non-crop vegetation in agricultural fields. In this vein, we assessed fall vegetation communities in 30 replicated cropping systems for both ecological and agronomic performance over three growing seasons in Denmark, wherein thirty management systems were applied to a cash crop sequence of spring barley *(Hordeum vulgare)*/oat *(Avena sativa)*/faba bean *(Vicia faba)*. Treatments included five cover crop systems [grass/clover (*Lolium perenne/Trifolium repens*) mixtures sown early- (MixE) and mid-season (MixM), radish (*Raphanus sativus*) sown mid-season (RadM) and post-harvest (RadL), and a no-cover control (NoCC)] implemented in all combinations of three tillage systems (no-till, surface, inversion) and two straw managements (retained, removed). Measured responses included cash crop yield, fall vegetative biomass and plant cover by species, spring weed species counts and pesticide use; ecological values of communities were estimated using published methods. The three-year study coincided with extreme weather years. Soil cover remained stable (~75%) across treatments and years, while fall biomass varied. Radish cover crops consistently increased fall biomass relative to NoCC, while the mixtures did not. Cover crop contributions to fall biomass were above >50% only in the RadM systems, with other vegetation communities being dominated by crop volunteers. Ecological value was highest for radish systems. All RadM systems consistently exhibited the highest crop yields, fall biomass and ecological value and did not increase perennial weeds compared to NoCC, but had no change in pesticide use. In contrast, while MixE reduced pesticide use compared to NoCC, it also produced variable and low fall biomass, had higher perennial weeds legacies with correlated with reduced crop yields, and supported lower-value but more complex plant communities. Overall, our study found radish cover crops exhibited more consistent agronomic and ecological benefits across all systems and years compared to the grass/clover mixes and NoCC, but require additional management compared to NoCC and do not inherently reduce pesticide loads. Our analyses underscore the complexity of assessing vegetation in cropping systems where multiple goals intersect.

**1 INTRODUCTION**

Environmental pressures resulting from population growth and climate change have led to a significant decline in global biodiversity (Ceballos et al., 2017; Dirzo et al., 2014). Given that >40% of habitable land is used for agriculture (Ritchie & Roser, 2019), agricultural management plays a crucial role in shaping biodiversity levels (Landis, 2017). Consequently, there is a growing need for agricultural systems that integrate ecosystem health and biodiversity conservation with commercial production objectives. In response, researchers are increasingly assessing non-crop plant communities (e.g., weeds) and their attendant management strategies for their potential ecological, as well as agronomic impacts.

In agricultural systems that utilize tillage and/or herbicides, studies have found fall cover cropping may have a minimal impact on subsequent weed communities due to the strong filters exerted by spring tillage and/or spring herbicide application (Adeux et al., 2021, 2023; Leskovšek et al., 2025; Rouge et al., 2023). It follows that fall non-crop vegetation may present a unique opportunity for optimization, allowing the expression of ecologically beneficial weeds without increasing the probability of future agronomic harm (Esposito et al., 2023). In this context, fall plant communities have the potential to offer a range of ecological and environmental benefits (Blaix et al., 2018; Gaba et al., 2020). The communities may serve as important promotors of plant diversity conservation (Fanfarillo & Kasperski, 2021), provide food sources for a high diversity of organisms (Balfour & Ratnieks, 2022; Marshall et al., 2003), reduce fall nitrate leaching (Miranda-Vélez et al., 2026; Sullivan et al., 2017), contribute to soil organic carbon (Jian et al., 2020), and mitigate soil erosion (Moreau et al., 2020). Several methodologies for estimating the potential values and future harms of non-crop vegetation have been proposed, each with different data requirements and outcomes considered (Bensch et al., 2025; Petit et al., 2011; Schatke et al., 2024; Storkey & Westbury, 2007; Yvoz et al., 2020). The lack of a universally accepted methodology precludes comparisons between studies, but within the context of a single study if the goals and assumptions of the estimating procedure are clearly articulated, estimating services and disservices of vegetation communities can provide valuable insight (Gentili et al. (in review)). Furthermore, as pesticide use has undesirable external impacts (CITE), linking the impacts of the pesticides associated with a given fall vegetation community provide additional accounting of the benefits and harms.

When considering fall vegetation, the interactions between cover crops, tillage and residue management is complex. While previous studies have looked at these interactions, it is most often within the framework designed with the goal of reducing the presence of weeds (e.g.,(Shrestha et al., 2002; Swanton et al., 1999; Weber et al., 2017)). It is therefore unclear how these factors might be combined to optimize the potential services provided by fall plant communities between cash crops. We hypothesized there would be tradeoffs between outcomes, with no single system offering the best performance in all desired areas.

To better understand these tradeoffs and the potential for optimizing fall non-crop vegetation services, utilizing a long-term (>20 years) study platform with six combinations of tillage and residue managements, we applied five cover cropping systems to a three-year sequence of crops. Using these 30 systems implemented over three cash crop growing seasons as a platform, we examined how, when compared to a no cover control, addition of cover crops to different tillage/residue cropping systems impacted:

1. Cash crop yields
2. Soil protection
3. Potential to reduce nitrate leaching
4. Potential plant community ecological value
5. Potential to cause future agronomic harm
6. Pesticide loads to human health and the environment

These outcomes were chosen to promote understanding of how cover cropping systems interact with tillage, residue removal, and weather in provision of various services and dis-services. We did not include the costs associated with cover crop implementation due to the complexity and highly contextual nature of such estimates. For example, in Denmark, cover crop implementations may be mandatory for receipt of subsidies that vary by farm, rendering the complexity of the actual cost calculations beyond the scope of this study. We provide an estimate of costs in supporting information, but exclude that information from this analysis.

**2 MATERIALS AND METHODS**

**2.1 Field management**

This study was conducted within a larger long-term crop rotation and tillage continuous experiment which was established in 2002 on a sandy loam at Flakkebjerg Research Centre, Denmark (55.317, 11.400). The 30-year average air temperature and precipitation for this site 8.9 degrees Celsius and 589 mm, respectively. Averaged across the trial site, soil texture in the top xx cm layer is 14.7% clay (<2 mm), 13.7% silt (2-20 mm), 42.6% fine sand (20-200 mm), and 27% coarse sand (200-2000 mm), with 1.2% organic carbon content (0-25 cm). The overall experimental design of the long-term experiment is a split-split plot with four replications. The main plot factor is crop and residue management (four levels), the subplot is primary tillage system (four levels) and the sub-subplot (six levels) was established to accommodate various sub-treatments within rotation and tillage combinations [see for example Melander et al. (2008)]. The cash crop sequence during the present study was spring barley (*Hordeum vulgare* L.) sown 19 April 2018, spring oat (*Avena sativa* L.) sown 4 April 2019 and faba beans (*Vicia faba* L.) sown 15 April 2020. Detailed tables and a visual of the study’s agronomic management are presented in supporting information, but are described here briefly.

**2.1.1 Study design**

For the purpose of the present study, two main plot treatments were selected that had the same sequence of crops but with different small grain straw managements that reflect common systems in Denmark: straw removed or retained. Therefore, in the present study, straw management composed the main-plot treatment. Three of the four tillage regimes were used for this study (more details below). Tillage subplots were 5 meters wide and 40 m long. Each tillage subplot was divided into two columns with three sub-subplots arranged within each column for a total of six sub-subplots that were 2.5 m wide and 12.5 m long (see supplementary material for a visual aid). One of the six sub-subplots was reserved for other sampling efforts, and a cover crop system treatment (five levels) was applied randomly to the remaining five sub-subplots. In summary, this experiment included all combinations of two straw-managements, three primary tillage systems, and five cover crop systems for a total of 30 treatments.

**2.1.2 Straw and tillage treatments**

The same straw managements and categorical tillage system treatments (no tillage, surface, inversion) have been in the same subplots since 2002. In the straw-removal treatments, following harvest of a small grain the residue (e.g., straw) was removed using a MACHINE, resulting in removal of approximately 60% of the biomass (CITE a CENTS modelling study for this 60% assumption). In the straw-retained treatments, following harvest of the grain residue was allowed to remain in the field. The exact machinery and timing of operations for each categorical tillage treatment have varied since 2002 (Scherner et al., 2016; Hansen et al., 2010). In the present experiment (2018-2020), plots under the inversion tillage treatment were moldboard plowed to a depth of 20 cm in the fall and harrowed to 3-4 cm depth in the spring before cash crop planting; crops were then sown with a traditional seed drill (Nordsten Lift-o-matic CLH300) with row spacings of 12.5 cm. For the surface tillage system (non-inversion), a Horsch Terrano 3 FX stubble tine cultivator was used to till to a depth 8-10 cm in the spring before cash crop planting. In both the no-till and surface tillage systems, crops were sown with a chisel coulter (Horsch Airseeder CO 3) with row spacings of 17.5 cm for spring oats, spring barley, and faba beans. Row spacings were different for the inversion tillage system due to differences in the equipment representing typical production environments for each tillage system.

**2.1.3 Cover crop treatments**

Starting in the spring of the 2018 growing season, five cover crop systems were randomly applied to the sub-subplots (Table 1). The same sub-subplot treatments were maintained for 2018, 2019 and were tracked until faba bean harvest in 2020. The sampling area for all measurements was located in the inner 1.5 m x 10 m area of the sub-subplots.

Table 1. Summary of the five cover crop systems

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| **Cover crop system abbreviation** | **Cover crop** | **Seeding rate** | **Seeding method and timing** |
| MixE | Perennial ryegrass *(grass; Lolium perenne)* and red clover *(clover; Trifolium pratense)* | 3 kg ha-1 grass + 8 kg ha-1 clover | Sown 1 cm deep in 12.5 cm rows between cash crop rows shortly after cash crop planting |
| MixM | Broadcast into standing crop approximately 14 days before expected cash crop harvest |
| RadM | Fodder radish *(Raphanus sativus)* | 14 kg ha-1 | Broadcast into standing crop approx. 14 days before expected crop harvest |
| RadL | Broadcast into the crop stubble post crop harvest |
| NoCC | None | - | - |

**2.1.4 Fertilizer and herbicides**

Mineral fertilizer was broadcast on spring barley plots on 17 April 2018 (126 kg N ha-1, 24 kg P ha-1 and 60 kg K ha-1); on spring oat plots on 3 April 2019 (80 kg N ha-1, 15 kg P ha-1 and 38 kg K ha-1 ); and on faba beans on 15 April 2020 (32 kg P ha-1 and 80 kg K ha-1).

Herbicide treatments reflected best practices and constraints imposed by both the tillage and cover crop system treatments. Each herbicide package (HP) is described in detail in supplementary material. In the no-till and surface tillage treatments, all plots were sprayed with HP1 (2018, 2019) or HP2 (2020) before cash crop planting. For the inversion tillage treatments, no herbicide was sprayed before cash crop planting. In 2018 (spring barley), to accommodate the presence of the grass and clover present in the Mix-early plots, those plots were sprayed on 16 May 2018 with an herbicide package that does not affect clover or grasses (HP3); all other plots were sprayed the same day with a different herbicide package (HP4). On 29 May 2018, all plots except the Mix-early plots were sprayed (HP5) to control Canada thistle (*Cirsium arvense*); Mix-early plots were not sprayed because HP5 would have terminated the cover crop. In 2019 (spring oat), on 14 May the Mix-early plots were again sprayed with the same herbicide package used in 2018 (HP3) while all other plots were sprayed with a different package (HP6) to….. Following faba bean planting in 2020, all plots were sprayed with HP7 on 6 May 2020 and again on 20 May 2020. On 2 June 2020, all plots were sprayed (HP8) to control wild oat (*Avena fatua*). All plots were managed identically for diseases and insect pests according to Danish standard recommendations and policies. Herbicide use data was translated into potential toxicity loads using the Danish Pesticide Load Indicator (PLI; Kudsk et al. 2018).

The long-term experiment is rainfed, but in 2018 an exception was made due to an extremely hot and dry early growing season. In order to maintain the long-term viability of the experiment, all plots were irrigated with 25 mm in early June to ensure the early establishment of all treatments. Irrigation was done with sprinklers mounted on a boom that was dragged through the experiment.

Weather data for the present study was obtained from the Danish Meteorological Institute's (DMI) Open Data API for the Flakkebjerg station (55.322, 11.388). The 30-year (1990-2020) mean annual temperature and precipitation for the site are 8.9 degrees Celsius and 589 mm, respectively.

**2.2 Measurements**

**2.2.1 Crop yields**

Each sub-subplot (net size 10 m x 1.5 m) was harvested for grain yield with a plot combine (spring barley: 8 August 2018, oat: 15 August 2019, faba bean: 24 August 2020 faba bean). Dry matter content was determined by a near-infrared spectroscopy analyzer (InfraTec™ 1241 Grain Analyzer, Foss A/S; [Buchmann et al., 2001](https://www-sciencedirect-com.ez.statsbiblioteket.dk/science/article/pii/S0167198710000541" \l "bib4)). Grain yields are reported on a dry matter basis.

**2.2.2 Fall vegetation**

Three categories of vegetation measurements were taken (Table 2) and are described in detail below.

Table 2. Summary of vegetation measurements

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| Measurement | Levels of measurement resolution |
| Fall ground cover (%) | Soil  Species (AVESA\*, CAPBP, CIRAR, EPHEX, HORVW, LOLPE, MATIN, PAPRH, RAPSR, TAROF, TRFRE)  Genus (GERSS, LAMSS, SENSS, VERSS) |
| Fall biomass (g m-2) | Cover crop  Other (all other biomass) |
| Spring weed counts (number m-2) Bo, just making sure the data you gave me is on a per m2 basis | CIRAR  EQUAR  Dicot  Monocot |
| \*EPPO code, see supporting information for Latin names | |

Ground cover composition was estimated from digital images taken in the fall (9 November 2018 and 1 November 2019) as done in Melander et al. (2013). Briefly, a 0.5 m2 quadrat was placed in the plot, and an image was taken from a height of 1 m above the center of the quadrat. Three images were taken in each plot, meaning 10% of the sub-subplot area was sampled (1.5 m2 per 15 m2 plot). Each image was subsequently overlaid with a grid consisting of 17 vertical and 17 horizontal lines, resulting in 289 intersections per image (Supporting information). Each intersection was classified as a soil or plant. Plant intersections were further classified to the species (12) or genus (4) level (Table 2). Percent coverage of each type was then calculated by dividing the number of touched intersections in that category by 289 intersections. For categorical analyses of percent cover, each species/genus was classified as ‘cover crop’, ‘volunteer’ or ‘other.’ Species/genus coverages were assessed (not including soil as a coverage category) for evenness by dividing Shannon’s diversity index by the natural log of species richness (Pielou, 1966).

The amount of aboveground vegetative biomass in each treatment was measured shortly after image collection for fall ground cover measurements (15 November 2018 and 13 November 2019, respectively). Two 0.5 m2 quadrats were randomly placed in each plot, and all aboveground biomass was cut at ground level and removed. The biomass samples from the two quadrats were combined, then separated into three fractions: cover crops, volunteers, and other in 2018. In 2019, biomass was only separated into two fractions (cover crops and other, the latter of which included both weeds and volunteers). Therefore, the categories ‘cover crop’ and ‘other’ were used for all aboveground biomass statistics (Table 2). The biomass fractions were dried in the oven at 80oC for 24 hours and weighed. Dry biomass for each category was converted to grams per m2.

The flora emerging in spring in the experimental plots was assessed on 22 May 2019 and 27 May 2020 after post-emergence weed control. Four categories were counted in three randomly placed 0.25 m2 quadrats per plot. The categories were dicots, monocots, Canada thistle (*Cirsium arvense*) and horsetail (*Equisetum arvense*), the latter two being problematic perennial weeds in Denmark (CITE). The spring counts were made to record whether there were any traceable effects from previous year’s cover crop treatments, with the goal of assessing whether the previous fall vegetation resulted in carry-over effects that were detectable even after weed control measures.

Potential ecological value was estimated using a methodology and database from Yvoz et al. 2021, including both pollinator value (the fall vegetation contained flowering plants) and ecological food web support including natural enemies (in the form of green plant and seed). Details on this calculation are presented in supplementary material but is described here briefly. The first component, potential benefits to pollinators, was comprised of three sub-indices representing (1a) the absolute benefit to bees (LATIN), (1b) bumble bees (LATIN), and (1c) hoverflies (LATIN). The second, potential benefits to food webs, was comprised of three sub-indices representing (2a) absolute contributions to farmland birds, (2b) carabids, and (2c) parasitic wasps. Organ level attributes reported by Yvoz et al. 2021 for 155 plant species were used to assign sub-index values. Out of the 11 species in our study, six had exact matches in the Yvoz et al. database. The volunteer crops (barley, oats) did not have values in the database, and were assigned values of 0. For the other species and genus (Table 2), the mean value for all species within that genus reported in the database were used. Each sub-index was reported in different units, so after each species/genus in the present study was assigned a value for each of the sub-indices, the sub-indices were scaled within the present study such that the maximum corresponded to a value of 1, and the minimum a value of 0. While this has the potential to exaggerate differences between values that are similar on an absolute scale, we observed at least one magnitude of variation in our dataset, suggesting the variation in sub-index values was meaningful (see supporting information). Sub-indices were summed to provide an estimate for each of the two indices (on a scale of 0-3) for each of the 16 species/genus observed in our study, and the sum of the two categories was assigned to each species/genus, representing the potential ecological services that could be provided by that species’/genus’ presence. These service values were weighted by the species/genus percent cover for each sample to calculate the fall vegetation community’s potential benefit to pollinators and contributions to organismal food webs.

**2.3 Multi-criteria summaries**

To summarise the performance of each system in the six metrics, we used scaling processes used in multi-criteria decision making (CITE). First, mean values for each cropping system were calculated in the performance metric’s original units. In all cases, a zero value performance has a physical interpretation, so we scaled the performances by dividing by the maximum performance value, thus retaining a meaningful zero interpretation and avoiding exaggeration of small differences in absolute performances – this scaled all performance values on a scale from 0 to 1. When performance metrics represented a situation wherein a higher value is less desirable (e.g., perennial weed counts), a value of one was subtracted from the performances, creating a mirrored scale such that a value of one always represents the most desirable situation. The total relative value of each system was calculated by summing the scaled performances together.

**2.4 Statistics**

All statistics and figures were done using R version 4.3.3 (R Core Team, 2024) relying heavily on the *tidyverse* meta package (Wickham et al., 2019), and additional packages (Silge & Robinson, 2016; Wickham et al., 2025; Wickham & Bryan, 2023) for data wrangling and visualization. Univariate statistical models were built using *lme4* (Bates et al., 2015) and *glmmTMB* (Brooks et al., 2017), and the best fit was chosen based on inspection of residual plots and AIC criteria (Bozdogan, 1987). The best fitting model was summarised using *emmeans* (Lenth, 2024). Multivariate models were built and analysed using *vegan* (Oksanen et al., 2024). Specific analyses are described in detail in supporting information, and all R code is available as part of the Github repository for this publication (available upon acceptance).

**3 RESULTS**

***3.1 Weather and crop yields***

The three years of production covered extreme conditions compared to 30-year averages; 2018 was the driest year of the past 30 years, and 2020 was the warmest. All production years started the season with more precipitation than average, but both 2018 (spring barley) and 2020 (faba bean) moved into drought conditions as the season progressed.

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| *Figure 1. (Top) Weather summaries comparing study years to 30-year averages. (Bottom) Study yields were comparable to mean yields observed in Denmark for each year (horizontal dashed lines) and were significantly impacted only by cover crop treatment, with the mid-season planted radish (RadM) treatment producing significantly higher yields (asterisk) compared to the other treatments in every year.* |

Yields varied significantly by crop (p<0.001) and by cover crop treatment (p<0.001), but did not vary significantly by any other factors or their interactions. In 2018 spring barley yields averaged 4.07 Mg ha-1, in 2019 spring oat yields averaged 4.28 Mg ha-1, and in 2020 faba bean yields averaged 3.47 Mg ha-1. On average, the RadM cover crop treatment exhibited 8% higher crop yields compared to all other cover crop treatments (p<0.001), which did not vary significantly from each other.

***3.2 Fall vegetation***

*3.2.1 Biomass*

The full statistical model showed complex interactions between variables, but with year having the largest impact (p<0.001). In 2018, average fall biomass production was 2.27 Mg ha-1, while in 2019 the average fall biomass production was less than half (0.99 Mg ha-1).

Residue treatment had a small but significant (p<0.001) main effect without significant interactions, with residue removal reducing fall biomass by 0.2 Mg ha-1 (SE:0.05). The effects of tillage and cover crop were amplified in 2018, with weaker effects in 2019, resulting in significant year interactions. Tillage effects were strongest in the RadM and RadL (p=0.048) compared to other treatments, and this effect was consistent across years. On average, increasing tillage intensity significantly decreased fall biomass by 27% and 9% when moving from no-till to surface tillage, and surface to inversion to surface, respectively. Growing degree days accumulated from cover crop planting to biomass sampling were not related to fall biomass values.

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| *Figure 2 (Top) Fall biomass was not related to growing degree days (GDDs, italic number in red) and exhibited complex treatment interactions (letters within a year indicate significant differences). (Bottom) Fall ground cover consisted mainly of cash crop volunteers, with cover crop coverage ranging from 1-72% (white labels).* |

*3.2.2 Cover*

The percentage of the soil covered by vegetation varied significantly by year (p=0.03) with a mean of 77% (SE:2%) soil exposure in 2018 and 70% (SE:3%) in 2019. Overall, soil coverage by cover crop species averaged 15%, but this varied significantly by cover crop treatment (p<0.001). Tillage, residue, nor their interactions had significant impacts on the coverage categories. The impact of cover crop treatment on cover crop coverage depended on the year, an effect driven by MixE: in 2018 the cover crops contributed an average of 21% (SE:5%) coverage, while in 2019 they contributed an average of 58% (SE:6%). In the other cover crop treatments, the contributions of the cover crop to coverage did not vary significantly by year, with RadM having the highest cover crop coverage (50%, SE:4%), followed by RadL (25%, SE:4%), MixM (7%, SE:3%) and NoCC (<1%, SE:3%). Cover crop coverage and volunteer/weed coverage was inversely correlated (ρ = -0.88).

*3.2.3 Fall vegetation community*

Communities were most strongly dictated by year of measurement due to the crop volunteer species varying by year. Model fit, convergence and interpretability were improved when models were fit to years individually, so results are reported for those models. Within a year, cover crop treatment explained 65-70% of the variance and had a significant effect on community structure (p<0.001), with tillage and straw removal treatments explaining less than 1% of the total variance each, respectively. The two cover crop mixture treatments (MixE and MixM) had communities distinct from the two radish treatments (RadM and RadL), with the NoCC communities being more similar to the mixture treatments in both years (Figure 3).

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| **Figure 3** *(Top)* Cover crop system had the largest impact on fall vegetation communities, with a minor impact of tillage system and straw removal *(Bottom)* Radish cover crop systems (RadM, RadL) had the highest potential ecosystem value, with the mixes (MixE, MixM) and NoCC systems having similarly low ecosystem value, due to a high percent coverage of low value crop volunteers in the community (see Figure 2). |

Year and cover crop treatment had significant impacts on the number of species observed in a community (p<0.001). The number of species observed ranged from one to eight, with a mode of two in 2018 and three in 2019. The MixE community had 1.4 (SE:0.2, p=0.02) and 1.5 (SE:0.2, p<0.001) times more species compared to the RadL and RadM communities, respectively, but the number of species in all other cover crop treatment comparisons were not significantly different. The evenness of the communities ranged from 0.09 to 1, and there was an amplifying interaction between cover crop treatment and year (p<0.001), evenness was generally higher in the radish cover crop treatments, followed by the early-planted mix, followed by the mid-planted mix and no cover treatments; this pattern was true regardless of tillage system, straw management, and year (supporting information).

Radish species were estimated to have the highest ecological value while spring barley and spring oat volunteers had no value (supporting information), resulting in treatments with high percent RAPSR coverage having the highest potential ecosystem value (Figure 3). While the mixes’ communities contained species with high ecological value (e.g., TAROF, LAMSS) that were absent in the radish systems, these high-value species had small contributions to the percent coverage, and therefore did not result in high estimated ecosystem support potential.

***3.3 Spring weed counts***

Total spring weed counts ranged from 28-1600 plants m-2, with a median of 296 plants m-2. There were complex treatment interactions, with a significant three-way interaction between year, tillage, and cover crop (p<0.001) and a significant two-way interaction between year and residue (p<0.001). Within the no-till system, MixE had significantly more weeds compared to all other treatments (p<0.001), while in all other tillage systems there were no differences between cover crop treatments; this effect was significantly more pronounced in 2019 (2.6-3.7 times more weeds) compared to 2020 (1.6-1.7 times more weeds), but the patterns were the same. The most dramatic differences were between MixE and RadM. The total number of weeds was highest in the inversion tillage systems, followed by surface tillage systems, with the no-till systems having the smallest number of total weeds; these effects were magnified in 2019 compared to 2020, and in 2020 the difference between no-till and surface tillage was borderline significant (p = 0.06). On average, inversion tillage had three and two times more spring weeds compared to the surface and no-till systems, respectively (**Figure 4**).

Both no-till and surface tillage had significantly increased numbers of perennial weeds compared to inversion tillage. Averaged over no-till and surface tillage treatments, the number of perennial weeds in the MixE was 11 times higher (SE:6; p<0.001) compared to the the NoCC treatment, and 2.6-8.6 times higher than the other cover crop treatments; these effects were erased in the inversion tillage treatment. The MixM had a borderline significant increase in perennial weeds compared to the NoCC (p=0.05), but all other treatments were not significantly different from the NoCC. The correlation between faba bean yields and annual weeds was not significant (ρ=0.002, p=0.98), while the correlation with perennial weeds was (ρ=-0.28, p<0.001).

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| **Figure 4.** *(Top)* Spring weed counts were significantly impacted by tillage system and cover crop treatment, with the early-planted mix exhibiting the highest perennial and overall weed count*(Bottom)* Faba bean grain yields were negatively correlated with the number of perennial weeds present in the spring. |

***3.3 Pesticide loads***

Pesticide usage (and therefore pesticide loads) differed by year, tillage system, and cover crop system; straw retention had no impact on the system’s pesticide use. In all systems and years, pesticide loads were lowest in the MixE treatments. Pesticide use was lowest in the inversion tillage system and did not differ between the surface and no-till systems (supporting information).

***3.4 Multi-criteria summary***

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| **Figure 5.** Summary of cropping systems’ performance in protecting soil (Soi), mitigation of fall nitrate leaching via fall biomass production (Bio), supporting ecosystems (Eco), grain production (Gra), perennial weed suppression (Per), and promoting human health and environmental safety (Saf); rows represent cover crop treatments, and columns represent tillage and small grain residue management systems. |

**4 DISCUSSION**

***4.1 Representativeness of results***

The average grain yields in each year of the present study were lower than national averages for the same crops in the same years [4.28 Mg ha-1 spring barley, 4.94 oats, and 4.08 Mg ha-1 faba bean, respectively (FAO, 2023)], but the maximum grain yields observed each year exceeded the national averages, demonstrating our results are reasonably representative of production environments. While the study was only in place for three cash crop cycles, the weather years represented a range of conditions that provide a reasonable amount of inference space (Figure 1) wherein our results are informative.

***4.2 Interactions between management practices***

Our results suggest radish cover crops, especially when planted mid-season, are a robust cover cropping system that performed well in the majority of performance metrics across tillage systems, straw managements, and weather years in a temperate oceanic climate (Peel et al., 2007). Other temperate areas in Europe have likewise found radish cover crop systems perform well in a variety of contexts (Slovenia one, others?)

While year had a strong impact on all outcomes in this study, it interacted with management practices by amplifying or dampening effects, rather than inducing cross-over interactions. A notable exception is performance of the early-planted cover crop mixture – in one year the resulting fall biomass contained very little contribution from the planted cover crop, while in another year it contributed over half of the total fall biomass (Figure 2). However, in both cases the absolute amount of cover crop biomass produced was still low.

The tillage system also amplified differences between cover crop treatments, but in general did not change cover crop systems’ biomass and cover rankings and had secondary impacts on fall communities compared to the cover crop treatment.

4.3 Fall community compositions

In our study, fall vegetation was mainly comprised of cash crop volunteers, which effectively competed with weeds (Figure 2). Previous studies in Denmark have shown that although fall communities dominated by cash crop volunteers reduce nitrate leaching compared to fallow land, radish cover cropping systems consistently reduce nitrate leaching compared to systems relying on spontaneous vegetation (CITE). Mitigation of fall nitrate leaching is strongly related to fall biomass production, and our results show that in addition to supporting higher biomass production that effectively competes with other vegetation (Lawley et al., 2012), radish cover crops may also support fall vegetation communities with higher potential ecological value compared to both no-cover and in-season planted cover crop mixtures. In our study, this was largely due to the radish cover crop replacing low-ecological value cash crop volunteers in the communities (Figure 3). While the other treatments supported more diverse fall communities, the communities were less even than the radish treatments; the contributions of species to soil cover was small compared to the cash crop volunteers, resulting in small contributions to the potential ecological value of the communities. Our research suggests that while policies currently support radish cover crops for reducing nitrate

The potential for radish cover crops to provide winter bridges for disease and insect pest propagation requires further investigation

Of the management practices investigated, straw management (retention or removal) had the weakest impacts on the outcomes evaluated in this study. This could be due to the incomplete removal of straw using a two-pass system wherein the straw is removed after grain has been harvested, resulting in around 60% of the straw being removed (CITE). A layer of straw mulch is therefore present in both systems, meaning light interception by the straw is similar with only the thickness of the layer varying.

In our study the cover crop mixtures performed poorly in the majority of performance metrics employed.

Our study adds to a growing body of research suggesting the use of cover crop mixes must be carefully and thoughtfully implemented, and the goals for the use of the mixes must be clearly articulated.

**5 CONCLUSIONS**

This section is optional. It is concluded that sown grass strips at arable field edges can enhance boundary plant diversity, particularly by increasing polycarpic species. Margin strips have a small influence on the weed flora of the crop edge, reducing weed cover of certain species, but have no influence on weed floras of field centres. Margins strips do not enhance rare arable weed species and may threaten the survival of such species, if strips are sited where rare species are known to occur in the seedbank at field edges. Field size and landscape context do not appear to influence weed diversity or cover, though crop type is an important influence on assemblages.

**ACKNOWLEDGEMENTS**

The study formed part of the EU Project XXX led by XX of XX University. The authors acknowledge the contributions of Eugene Driessen, Karen XX, XXX who collected all data presented and whose field and laboratory expertise contributed significantly to this work.

**CONFLICT OF INTEREST**

Please state any conflicts of interest.

**REFERENCES**

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**TABLE S1** Terms selected in a regression type analysis using REML to predict *A. myosuroides* head densities from soil properties.

**FIGURE S1** Maps showing the kriged soil moisture content (0–10 cm) in each of the 5 fields (a) Radbrook (b) Haversham, (c) Harpenden, (d) Redbourn, (e) Ivinghoe, soil moisture is gravimetric in all cases except Radbrook where the volumetric moisture content is shown.

**Figure legends**

**FIGURE 1** Canonical Correspondence Analysis ordination of the flora from the boundaries (◊), 6 m margins (o), crop edges (×) and crop centres (∇) of paired arable fields in southern England. Data are based on mean species cover from three 5 m2 quadrats per location. The first two axes explain 39% of the species-environment relations.

Colour figures

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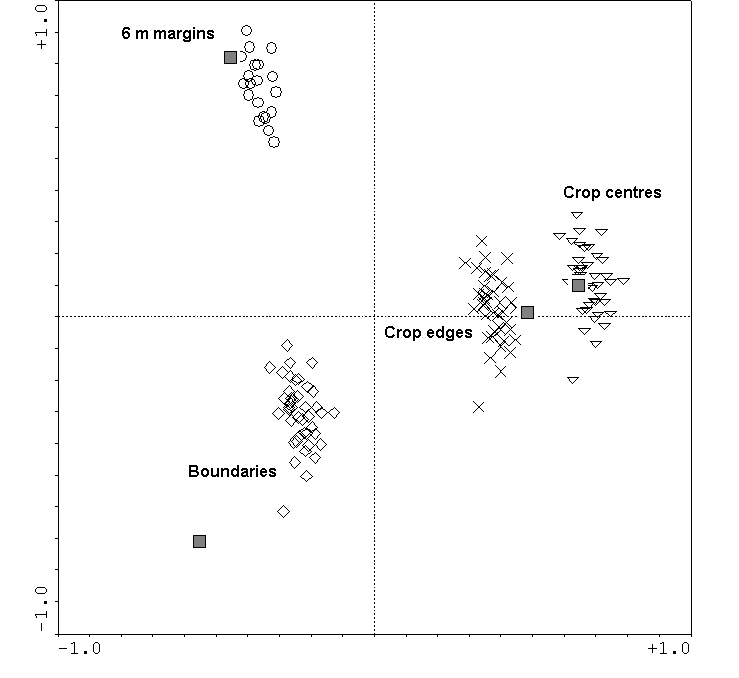
**TABLE 1** Mean values of land cover and farm inputs for field sites in three landscape types. NS = not significant

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Landscape type | | |  |
|  | Small | Intermediate | Open | SED (df = 18) |
| Mean farm size (ha) | 335 | 626 | 1109 | 234 |
|  |  |  |  |  |
| Variable (for 500 m circle) | |  |  |  |
| Mean field size (ha) | 5.4 | 9.1 | 13.0 | 0.99 |
| No. fields | 20.7 | 18.2 | 11.8 | 2.604 |
| No. grass fields | 7.5 | 8.4 | 2.0 | 2.058 |
| Mean arable field size (ha) | 6.4 | 11.8 | 14.3 | 2.206 |
| Mean grass field size (ha) | 3.4 | 6.0 | 3.3 | NS |
| % arable | 65.0 | 59.1 | 88.1 | 7.19 |
| % grass | 22.8 | 29.7 | 4.0 | 0.613 |
| % buildings, roads | 4.6 | 3.8 | 1.6 | 0.811 |
| No. pesticide (a.i.) applications per season | 5.3 | 7.1 | 5.9 | NS |
| Nitrogen fertiliser (kg ha-1) | 148 | 242 | 174 | NS |

**TABLE 2** Plant species richness (mean number of species per 50 m2 sample) in field boundaries and crop centres with and without sown 6 m margin strips (data including crop species)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Landscape | Small | Intermediate | Open | Mean |
| Boundary | 6 m margin | 35.57 | 35.71 | 28.29 | 33.2 |
|  | Control | 25.86 | 29.00 | 28.29 | 27.7 |
| Crop centre | 6 m margin | 10.71 | 7.43 | 12.57 | 10.2 |
|  | Control | 12.71 | 9.43 | 11.71 | 11.3 |

Overall SED = 2.058; df = 54; SED for means = 1.46: df = 54.



**FIGURE 1**