**Multi-criteria evaluation of fall vegetation services in 30 cropping systems using four farmer typologies**

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# Abstract (<250 words)

1. Purpose

With increasing environmental pressures from population growth and climate change, there is growing interest in designing cropping systems that balance productivity and environmental impacts. However, assessing cropping systems using multiple criteria introduces greater complexity, requiring new frameworks to facilitate meaningful interpretations.

1. Experimental

This study evaluated fall vegetation communities and attendant agronomic and environmental performance of 30 replicated cropping systems over three growing seasons in Denmark. Treatments included five cover crop systems [*Lolium perenne* and *Trifolium repens* mixture sown early- and mid-season, *Raphanus sativus* (radish) sown mid-season and post-harvest and a no cover crop control] embedded within every combination of three tillage approaches (no-till, surface, inversion) and two residue managements (retained, removed). Measurements captured a range of agronomic, ecological, and environmental outcomes. Select outcomes were used as indicators for five utility categories used to define farmer typologies: (i) cash crop grain yields (productivity), (ii) perennial weed abundance (agronomic impacts), (3) fall vegetation aboveground biomass (social identity - regulatory), (4) fall plant community ecological value (social identity - steward), and (5) pesticide toxicity loads (social identity, health). Multi-criteria decision-making was applied, utilizing unique outcome weights derived from four farmer typologies to calculate a typology-specific utility for the 30 systems.

1. Results

The study coincided with extreme precipitation years. Only the radish cover crops consistently increased fall biomass compared to the no-cover control. Radish treatments produced neutral vegetation communities (IS THIS TRUE STILL), while the plant communities in the mix and no cover crop treatments had species with potentially high ecological benefits, but also increased perennial weeds. Across tillage, residue, and weather the mid-season planted radish exhibited the highest fall biomass, high crop yields, and no increase in perennial weeds compared to the no cover control, but had moderate to high pesticide toxicity loads and produced fall vegetation with low potential ecological value. Conversely, the early planted mix had low to moderate fall biomass, moderate crop yields, x times more perennial weed increases compared to other treatments, but had low pesticide toxicity loads and supported fall vegetation that had high potential ecological value. Moreover, mid-season radish cover crop systems had high utility for all typologies, while early-planted cover crop mixtures exhibited the lowest utilities.

1. Novelty

These results underscore the complexity of balancing multiple goals, highlighting the interplay between biophysical, ecological and agronomic outcomes. In this region, mid-season planted radish cover crops may exhibit more consistent benefits across cropping systems, weather conditions, and farmer typologies compared to grass/clover mixtures. The use of farmer typologies to build weighting schemes presents a promising method for evaluating cropping systems tradeoffs.

Keywords: cover crops, farmer typologies, multicriteria decision-making, cropping systems, tillage

# Highlights:

3-5 bullet points, max 85 characters

Requires a graphical abstract

# Introduction

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Environmental pressures resulting from population growth and climate change demand that agrosystems better balance productivity with their wider environmental impacts (CITE). While agrosystems have led to a significant decline in biodiversity (CITE). Given the extensive land area dedicated to arable agriculture, agricultural management plays a crucial role in shaping biodiversity levels (CITE). 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 impacts on biodiversity and the environment. This requires estimating both the ecological value of these communities within and beyond agro-ecosystems, their possible negative impacts on crop production, and the ecological impacts of their management (Esposito et al., 2023; Petit et al., 2011; Storkey and Westbury, 2007).

Non-crop communities embedded within production fields may offer a range of ecological benefits. They may serve as important promotors of plant diversity (CITE), provide food sources for a high diversity of organisms (Balfour and Ratnieks, 2022; Marshall et al., 2003), offer habitat (CITE), reduce nitrate leaching (Wortman, 2016) *(Blaix et al., 2018; Huang et al., 2018b)* (Sullivan et al., 2017), contribute to soil organic carbon (Jian et al., 2020), or mitigate soil erosion (Moreau et al., 2020)

Pick citations from this blurb to add:

*However, weeds also provide services for agroecosystems, promoting plant biodiversity and feeding other organisms potentially valuable to crop production (e.g pollinators, beneficial predators such as carabid beetles) (Petit et al., 2011; Kulkarni et al., 2015; Rollin et al., 2016).*

In agricultural systems that utilize tillage and/or herbicides, studies have found fall cover cropping has a minimal impact on subsequent weed pressure due to the strong filters exerted by spring tillage or herbicide application (Adeux et al., 2023; Rouge et al., 2023) (Adeux et al., 2023, 2021) OTHERS. It follows that fall non-crop vegetation may present a unique opportunity for optimization, allowing the expression of ecologically beneficial weeds without resulting in future agronomic harm, in addition to providing services such as soil cover and soil nitrate retention (CITE).

Some studies have shown fall fallow can result in plant communities that may offer equal or even superior benefits when compared to communities resulting from planting cover crops, but only in certain years and/or cropping systems (CITE). The interaction between cover crops, tillage and residue management is complex, and it is unclear how these factors might be combined to optimize the services provided by fall non-crop vegetation, and how reliable these outcomes are in different weather years. To better understand the potential for optimizing fall non-crop vegetation services, we embedded five cover cropping systems within six combinations of tillage and residue managements, resulting in 30 unique cropping systems. Using these 30 systems as a platform, the objectives of this study were to examine how, when compared to a no cover control, addition of cover crops and their attendant management impacted:

1. Soil protection
2. Reduction of nitrate leaching
3. Plant community ecological value
4. Cash crop yields
5. Pesticide toxicity loads to the environment and human health
6. Future agronomic harm potential

These objectives were designed to promote understanding of how cover cropping systems interact with tillage, residue removal, and weather in provision of various services and dis-services. We chose to focus on the biophysical outcomes of the systems, and do not include the economics of the various systems as a response variable because these can vary based on sociopolitical conditions, policies, and subsidies (Kathage et al., 2022).

Multicriteria decision analysis is a tool for evaluating and comparing different alternatives to facilitate informed decision-making when presented with complex, often conflicting objectives. It is widely applied in business, government, but has had limited application in agricultural settings (CITE). One barrier may be the requirement that the importance of each objective be reflected by weights, which are subjective and therefore context specific.

Something about farmer typologies….Typologies xx have been used to assess cropping system suitability under climate stress (Curtis et al., 2024), design agricultural policy (Huber et al., 2024), and to target conservation activities (Upadhaya et al., 2021).

To summarise

# 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). Averaged across the trial site, soil texture in the top 0-25 cm 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(Scherner et al., 2016). The overall experimental design of the long-term experiment is a split-split plot with four replications. The main plot factor is cropping system (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 supplemental material, but are described here briefly.

### 2.1.1 Study design

For the purpose of the present study, two cropping systems were selected that had the same sequence of crops but with different small grain residue managements that reflect common systems in Denmark: straw removed or retained. Therefore, in the present study, residue 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 (Figure 1).

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|  |
| Figure 1. The present study included all combinations of two residue, three tillage, and five cover crop treatments, resulting in 30 unique cropping system treatments. |

### 2.1.2 Residue and tillage treatments

The same residue managements and categorical tillage system treatments (no tillage, surface, inversion) have been in the same subplots since 2002. In the residue-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 residue-retained treatments, straw was allowed to remain in the field following grain harvest. 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 equipment representing typical production environments for each tillage system.

### 2.1.3 Cover crop treatments

Starting in 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

|  |  |  |  |
| --- | --- | --- | --- |
| Cover crop system name | Cover crop | Seeding rate | Seeding method and timing |
| EarlyMix | Perennial ryegrass *(grass; Lolium perenne)* and red clover *(clover; Trifolium pratense)* | 3 kg ha-1 grass + 8 kg clover ha-1 | Sown 1 cm deep in 12.5 cm rows between cash crop rows shortly after cash crop planting |
| MidMix | Broadcast into standing crop approximately 14 days before expected cash crop harvest |
| MidRad | Fodder radish *(Raphanus sativus)* | 14 kg ha-1 | Broadcast into standing crop approx. 14 days before expected crop harvest |
| LateRad | 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 (see Figure 2). 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.

## 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 (8 August 2018 barley, 15 August 2019 oat, 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.

### Vegetation measurements

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

Table 2. Summary of vegetation measurements

|  |  |
| --- | --- |
| **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 supplemental material for Latin names | |

#### 2.2.1.1Fall ground cover

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. 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, each species/genus was classified as ‘cover crop’, ‘volunteer’ or ‘other.’

#### 2.2.1.2 Fall biomass

The amount of aboveground plant biomass in each treatment was measured 15 November 2018 and 13 November 2019, respectively, shortly after fall ground cover images were collected. 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, weeds and volunteers 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 statistical analyses (**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.

#### 2.2.1.3 Spring weed counts

The weed flora emerging in spring in the experimental plots was assessed on 22 May 2019 and 27 May 2020 after post-emergence weed control. Four weed categories were counted in three randomly placed 0.25 m2 quadrats per sub-subplot (representing 5% of the sub-subplot area). The categories were dicots, monocots, Canada thistle (*Cirsium arvense*) and horsetail (*Equisetum arvense*). The weed counts in spring were affected by the earlier herbicide spring applications, and the goal was to assess whether the previous fall vegetation resulted in carry-over effects that were detectable even after weed control measures.

#### 2.2.1.4 Potential ecological services

Potential ecological value was estimated using a methodology derived from that of Yvoz et al. 2021, including both pollinator value (as the fall vegetation did contain flowering plants) and ecological food web support (as the fall vegetation did contain plants that went to 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) parasitoid 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 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 supplemental material). 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/genuses observed in our study, and the maximum of the two categories was assigned to each species/genus, representing the maximum ecological services that could be potentially provided by that species’ presence. These service values were weighted by the species/genuses’ percent cover for each sample to calculate the fall vegetation community’s potential benefit to pollinators and contributions to organismal food webs.

### 2.3 Statistics

All statistics and figures were done using R version 4.3.3 (CITE) relying heavily on the *tidyverse* meta package (CITE), and several additional packages (CITE gh4x, readxl, others?). For all statistical models, several models were tested using lme4 (CITE), nlme (CITE), and glmmTMB (CITE) to account for potentially non-normal error distributions and unequal variances, and the best model fit was chosen based on inspection of residual plots, AIC criteria (CITE), and interpretability. Only the best fit model is described here, but the R code that includes model testing is available as part of the github repository for this publication (CITE). Marginal means and contrasts were estimated using *emmeans* (CITE) and significance letters were assigned using the *multicomp* package (CITE).

Crop yields were modelled using lme4 with main effects of crop, tillage, residue, and cover crop treatment and all possible interactions with a random effect of block, and a random effect of tillage nested within residue nested within block.

For total fall biomass, a full model with all fixed effects and their interactions and a fully nested random effects did not converge. To simplify the nested random effects structure, the variance of each random effect was inspected individually. Different random effects model structures were tested using AIC criteria, and a model was selected that accounted for random effects of block, tillage, and cover crop nested within tillage. Year had an overwhelmingly large effect, and due to the large number of factors in order to assign significance letters in an interpretable way, two separate models were fit for each year. For the single year models, total biomass was modelled using glmmTMB with main fixed effects of tillage, residue, and cover crop and all of their interactions with random effects for block, tillage, and cover crop nested within tillage. Significance letters were assigned to each group within each year using the *emmeans* and *multcomp* packages (CITE).

For the proportion of fall biomass, the cover crop proportion was modelled using glmmTMB with fixed effects of tillage, cover crop, residue, and a year factor with a random effect of block using a binomial error distribution (logistic regression) and .

For the spring weed counts, the total number of weeds was modelled using *glmmTMB* with fixed effects of tillage, cover crop, residue, a year factor and all of their interactions with a random effect of sub-subplot nested within subplot nested within plot, a term to adjust for zero-inflation, and a negative binomial error distribution (first order). Additionally, the proportion of the spring weeds that were perennials was modelled using a beta family error distribution and an adjustment for zero inflation. Results were summarized using *emmeans*.

### 2.4 Multi-criteria comparisons

To facilitate meaningful summaries of and comparisons between the 30 cropping systems, we assigned weightings to five outcomes measured in the present study. Each set of weightings was chosen to represent five major categorical measures whose relative importance differ between farmer typologies as identified and described by Upadhaya and colleagues (Upadhaya et al., 2021).

# Results

## Weather

All three production years were warmer than the 30-year average (Figure 1)

A graph of different weather conditions

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**Figure 1.** Weather for the three production seasons captured a range of precipitation and temperature conditions.

## Individual measurement outcomes

Due to the potential for complex four-way interactions, results are presented here as summaries of statistical results. Detailed statistical tables and descriptions are presented in Supplementary Materials.

### 3.2.1 Yields – DONE – MidRad was higher

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 oat yields averaged 4.28 Mg ha-1, and in 2020 faba bean yields averaged 3.47 Mg ha-1. The average grain yields 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. On average, the MidRad cover crop treatment exhibited 8% higher crop yields compared to all other cover crop treatments (p = XXX); all other cover crop treatment yields did not vary significantly from each other.

### Fall biomass

Year had a significant spreading interaction with tillage (p<0.001) such that tillage treatment impacts were stronger in 2018 (when fall biomass production was higher, averaging 2.27 Mg h-1) compared to tillage effects in 2019 (when fall biomass averaged 0.99 Mg ha-1). As tillage intensity increased, fall biomass significantly decreased, with inversion tillage producing on average 66% (2018) and 77% (2019) of that produced in the no-till treatments.

Year also had a significant interaction with cover crop treatment (p<0.001), but with cross-over effects driven by the NoCC treatment. In 2018, the NoCC treatment produced the second highest biomass of all of the cover crop treatments (2.36 Mg ha-1, SE:9.4), while in 2019 it produced the lowest amount of biomass amongst all of the cover crop treatments (0.64 Mg ha-1, SE:9.4). MidRad produced the most biomass in both years, and the lowest producing cover crop treatment was MixE in 2018 and NoCC in 2019.

A graph of different colored bars

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Figure 2. Fall biomass was significantly higher in 2018, instances with different letters indicate significant differences at p<0.05

Residue management had a significant impact on fall biomass (p<0.001), but did not interact with any other factors; retention of residue increased fall biomass by a mean of 208 kg ha-1 (SE:4.9).

The effect of tillage treatment was significantly more amplified in some cover crop treatments (p=0.04), but the general patterns were consistent across cover crop treatments: no-till resulted in the largest amount of fall biomass, followed by surface tillage, with inversion tillage producing the lowest amount of fall biomass (Figure 2).

The effect of cover crop on total biomass also differed significantly by year (p<0.001)

depended on the cover crop treatment, but only in amplification of patterns reducing tillage significantly increased fall biomass production in all cover crop treatments, although the effect was more amplified in certain treatments certain cover crop treatments amplified the effect of tillage (p=0.048), and removal of residue nor its interactions had any significant effect and had significant interactions with both cover crop treatment (pxx) and tillage (xx), but not residue management (XX). For simplicity in interpretation, we present the results separately by year. In 2018, average fall biomass production was 2.27 Mg ha-1. There was a significant amplifying interaction between tillage and cover crop treatment (p=0.048), and removal of residue nor its interactions had any significant effect. No-till significantly increased fall biomass in all cover crop treatments compared to surface and inversion tillage, but this effect was most amplified in the RadM cover crop (Figure 2). 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. In 2019, fall biomass production averaged 0.99 Mg ha-1, and while there was a significant three-way interaction between tillage, residue, and cover crop (p= 0.03), it was soley due to the MixMid treatment, where residue removal had no effect regardless of tillage in the surface tillage, where residue removal . The radish cover crops (RadM and RadL) followed the same pattern as in 2018 with regards to tillage (increasing biomass with decreasing tillage intensity), while the other cover crop treatments had varying patterns with small differences that were not physically relevant magnitudes.

Radish cover crops consistently contributed over 50% of total fall biomass, while the mixes’ contributions varied (0–80%). The mid-season planted mix (MixMid) never contributed more than 20% of the total fall biomass.

### Soil cover

Percent soil cover did not vary by treatment or year (p = x-x), averaging 75% (Figure 2). Overall, volunteers contributed the highest coverage percent, followed by cover crops (X%) with minimal weed coverage (X%), but the relative contribution of each category varied by cover crop treatment (p = xx), year (p, ), blah blah.

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|  |
| Figure 3. Soil exposure (dark brown) was not impacted by any treatments and averaged 25%; crop volunteers (light yellow) contributed significantly to soil coverage in all treatments, with other vegetation (red) contributing minimal soil coverage. Crop residue retention (+res) or removal (-res) had no significant impact on coverage categories. |

### Fall vegetation community

A screenshot of a graph

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The volunteers (barley or oat), the radish, and the grass cover crop were neutral with regards to both potential ecological contributions, as well as potential agronomic harm. Therefore, and the

Volunteer crops and radish are neutral vegetation types that offer low services, but also low potential dis-services, while the X weed species/genuses offered a range of services and dis-services. When analyzed on a community level, the treatments resulting in the highest weed coverage therefore corresponded to the treatments with the highest potential services (Figure 2).

Ecosystem values

Potential contributions to pollinators and ecosystems were calculated by multiplying the value of an individual species/genus by the percent cover. The maximum value (either pollinators or ecosystems) was assigned as the estimate of potential benefits from the fall vegetation, and agronomic harm was used as the estimate of potential disservices. The number of stems of Canadian thistle present after two

Radish treatments produced neutral vegetation communities, with neither high potential benefits nor harms. In contrast, the mixes and no cover crop treatments displayed both high potential harm and high potential benefit.

### Spring weed counts

Spring weed counts ranged from 28 to 16000 plants m-2, with a median value of 296 plant m-2. The patterns in the total number of weeds by cropping system was the same between years, but the patterns were amplified in the first year (2019) compared to the second (2020). To simplify interpretation, results are reported as the means over the two years. The total number of spring weeds increased as the intensity of the tillage system increased. The number of weeds in the surface and inversion tillage treatments were two and three times higher than in the no-till treatments (p>0.001), respectively. Of the cover crop treatments, only the MixEarly cover crop treatment impacted the total weed counts, and only in the no-till treatment where it increased the total weed counts by 2 to 2.5 times compared to the other cover crop treatments (p>0.001)

A graph of different types of crops

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## Cropping system utilities

Using the available measurements, appropriate proxies for each of the five utility categories were chosen. Grain yields were chosen to represent profit motivation. All farmers must operate in a profitable manner…need to explain this better. Perennial weeds are a major agronomic concern for all types of farmers (CITE), so spring perennial weed counts were chosen to represent the agronomic impacts category. Social identity was divided into three utility categories: regulatory, stewardship, and health. Farming regulations are most often practice-based (rather than outcome-based), so while all farmers are assumed to follow regulations, certain farmer typologies focus on achieving the desired outcomes from the regulations rather than focusing on the practices themselves. In Denmark, regulations are built around ensuring nitrate is not lost from fields during the fall, and therefore entails requirements related to practices that, on average, produce sufficient fall vegetation to reduce nitrate leaching to an acceptable level (CITE). Fall vegetation biomass was therefore used to represent the regulatory component of social identity. Stewards tend to value the ecosystem services provided by agriculture, and was therefore represented by the ecosystem value of the fall vegetation communities. Impacts on human health were represented by pesticide toxicity loads. Weightings were chosen to exaggerate differences between typologies and maximize representation of the decision space (**Table 3**).

**Table 3.** Summary of the four farmer typologies and their assigned value weightings for five utility categories and the measurements used to represent them.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Farmer type** | **Profit motivations** | **Agronomic impacts** | **Social identity - Regulatory** | **Social identity - Stewardship** | **Social identity - Health** |
| *Grain yield* | *Spring perennial weed count* | *Fall vegetation biomass* | *Ecosystem services of fall vegetation* | *Pesticide toxicity loads* |
| Conservationist | 40 | 20 | 20 | 10 | 10 |
| Deliberative | 40 | 40 | 10 | 5 | 5 |
| Traditionalist | 50 | 35 | 15 | 0 | 0 |
| Productionist | 70 | 30 | 0 | 0 | 0 |

# Discussion