**Agronomic and ecological impacts of fall vegetation in 30 cropping systems**

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**Abstract (250 words max)**

With increasing environmental pressures from population growth and climate change, interest is growing in holistically evaluating non-crop plant communities. This study assessed fall vegetation communities and attendant agronomic performance in 30 replicated cropping systems over three growing seasons in Zealand, Denmark. 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)] combined with three tillage approaches (no-till, surface, inversion) and two residue managements (retained, removed). Measured responses included crop yield, fall biomass, plant cover, and spring weed counts. The study coincided with extreme drought (2018) and high precipitation (2019). Soil cover remained stable (~75%) across treatments and years, while fall biomass varied. Radish cover crops consistently increased biomass relative to NoCC, while the mixtures did not. Vegetation communities were dominated by crop volunteers, and ecological value estimates were highest in radish treatments due to the high value assigned to radish. Across tillage, residue, and weather, RadM consistently offered the highest fall biomass, crop yields, and ecological value, without increasing perennial weeds compared to NoCC. In contrast, MixE produced variable fall biomass, had higher perennial weeds which reduced crop yields, and supported more complex but lower-value plant communities. Overall, in our study we found RadM exhibited more consistent agronomic and ecological benefits compared to the mixes and NoCC, but 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 (CITE). Given the extensive land area dedicated to arable agriculture in Europe (CITE), 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 potential ecological, as well as agronomic impacts.

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 this context, fall plant communities may offer a range of ecological and environmental 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 *(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). The potential agronomic harm they may present must also be taken into account, considering both current risks and legacies of risk (CITE). Estimating ecological value and agronomic harm of species and communities is tricky. Several frameworks have been proposed, but each presents limitations based on data availability, generalizability, and XXX (Esposito et al., 2023; Petit et al., 2011; Storkey and Westbury, 2007). The lack of a universally accepted methodology precludes comparisons between studies, but within the context of a single study, a given approach may provide useful insight (XX).

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 plant communities between cash crops. We hypothesized there would be tradeoffs between outcomes, with no one system offering the best performance in all desired areas.

To better understand these tradeoffs and 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, 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 reduction of nitrate leaching
4. Potential plant community ecological value
5. Potential to cause future agronomic harm

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 actual cost calculations beyond the scope of this study. We provide an estimate of costs in supplemental material, but exclude that information from this analysis in order to focus on biophysical outcomes.

**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). Averaged across the trial site, soil texture 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 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 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 (do we have any pictures of the straw retained and straw removed treatments, so we can see how the ground was still covered by little bits of straw after straw removal? CITE a CENTS modelling study for this 60% assumption). In the straw-retained treatments, harvest 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 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 |
| MixE | 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 |
| 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 (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.

**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

|  |  |
| --- | --- |
| 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 | |

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.’

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, 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.

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 plot. The categories were dicots, monocots, Canada thistle (*Cirsium arvense*) and horsetail (*Equisetum arvense*). The spring counts were made to record whether there were any traceable effects from previous year’s cover crop treatments. 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.

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**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), and the best fit was chosen based on inspection of residual plots and AIC criteria (CITE). Only the best fit model is described here, but the R code is available as part of the github repository for this publication (CITE). Marginal means and contrasts were estimated using emmeans (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, first a universal model was fit that included fixed effects of a year factor, tillage, residue, and cover crop, but every term had a significant interaction with year. To simplify interpretation, a separate model was then fit separately to each year’s data. In both years, 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 multcomp package (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 family with a logit link.

**3 RESULTS**

Results should be separated from discussion. Present the key analysed results objectively. Do not repeat data in both tables and figures.

Analyses of land cover, pesticide and fertiliser use between the sites showed some differences associated with the field size/landscape type (Table 1). There were no significant differences associated with farms with and without 6 m margins. Clearly, farm size and mean field size varied with landscape. Small and intermediate landscapes had similar proportions of arable and grassland, but open landscapes were dominated by arable cropping. There were no significant differences in amounts of nitrogen or pesticides between areas, though the data were highly variable.

*Table 1 near here*

Plant diversity in the sown 6 m margins averaged 17.8 species per 15 m2 sample. Species richness, total cover, cover of monocotyledons and cover of dicotyledons in the strips were unaffected by landscape type, indicating that there was little bias in types of seed mixture used to establish 6 m strips across field sizes and landscapes. Analysis of the flora of 6 m margins (data not shown) indicated that there were differences in plant communities in the sown strips, with site separations reflecting the dominant grass species present. Nevertheless, plant species richness was not clearly correlated with the type of dominant grasses present.

Analysis of the species richness of the flora of field boundaries and crop centres, using the full dataset of 10 quadrats per site, indicated significantly greater biodiversity in the boundary of margins adjacent to sown 6 m margin strips (Table 2), but no statistical difference between landscapes.

*Table 2 near here*

Analyses of the cover of the four plant species in the boundary, crop edge and crop centre showed there were significant effects of the presence of the 6 m strip on A. sterilis in all three locations (Table 3). Galium aparine was unaffected by the margin strips, but E. repens, a rhizomatous grass weed, was less abundant in crop edges adjacent to grass strips. The perennial grass F. rubra, was more abundant in boundaries and crop edges adjacent to grass margins, possibly reflecting the presence of the species in some seed mixtures.

*Table 3 near here*

Multivariate analysis of the full data, based on means of three quadrats per location, showed the expected differences between the flora of the boundary and the crop (Fig. 1). Axis 1 of the ordination divided the annual weed flora of the crop edge and crop centre from the more perennial flora of the boundaries and sown 6 m margins. Axis 2 divided the 6 m margins from the boundary flora. The first and second axes explained 13.6% of the species data and 38.9% of the species-environment relations, with eigenvalues of 0.66 and 0.38 respectively. The locations provided the major explanatory variables, together with crop types. There was only one weakly significant landscape variable.

*Fig 1 near here*

**4 DISCUSSION**

Discuss the implications of the results in the context of previous research. Critically evaluate the methods employed. There were on average significantly more plant species in the field boundary hedge bases adjacent to sown grass strips, compared with situations where arable crops were grown up to the boundary. There is evidence that agrochemicals, particularly fertilisers and herbicides, can have adverse impacts on the flora of field boundaries (Kleijn & Snoeijing, 1997; Gove et al., 2007). Therefore, it is likely that the difference in species diversity is a reflection of contrasting levels of disturbance between the two boundary types. This is borne out by the greater cover of polycarpic plant species in sites with the margin strips. Polycarpic species are perennials, whilst the monocarpic species are annuals and biennials that depend on seedling recruitment and, by implication, disturbance to allow that recruitment. The margin strips, because farming operations take place further away, may provide protection to the hedge base. Over time, this would favour polycarpic species by reducing the occurrence of safe sites for seedling establishment of weedy annuals and biennials. These results concur with the results of Moonen & Marshall (2001) from a single farm study and confirm the hypothesis that margins strips can enhance boundary plant diversity.

**4.1 Landscape, field size and weed assemblages**

There has been a trend of increasing field size over the past century. Removal of hedgerows and field boundaries has facilitated the use of larger and more efficient farm machinery. Over time, one might expect that the processes of field enlargement, uniformity of management and dispersal, might impact on field flora assemblages. Current management, in terms of pesticide and fertiliser applications, was apparently similar across the studied landscapes. However, the test of effect of landscape structure gave no convincing evidence of differences in weed diversity or weed cover associated with field size.

Total species numbers recorded and diversity partitioning of the crop centre flora also indicated no effects of landscape. In comparison with a study of organic and conventional arable flora in Germany (Clough et al., 2007), the data here from conventional arable fields showed much lower α diversity (12% v. 40%). Most diversity was provided by β diversity, indicating that weed assemblages showed greatest variability from field-to-field and between regions. Field-to-field variability in weed assemblages is well-known (e.g. Marshall & Arnold (1994)). There was a trend for greater crop cover with increasing field size, perhaps reflecting efficiencies in crop establishment and management in larger farm enterprises. The lack of field size effects on weed floras indicates that they probably are not sensitive to factors operating at the landscape scale, at least within predominantly arable landscapes (≥60%).

**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.

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**CONFLICT OF INTEREST**

Please state any conflicts of interest.

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**Supporting Information**

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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.

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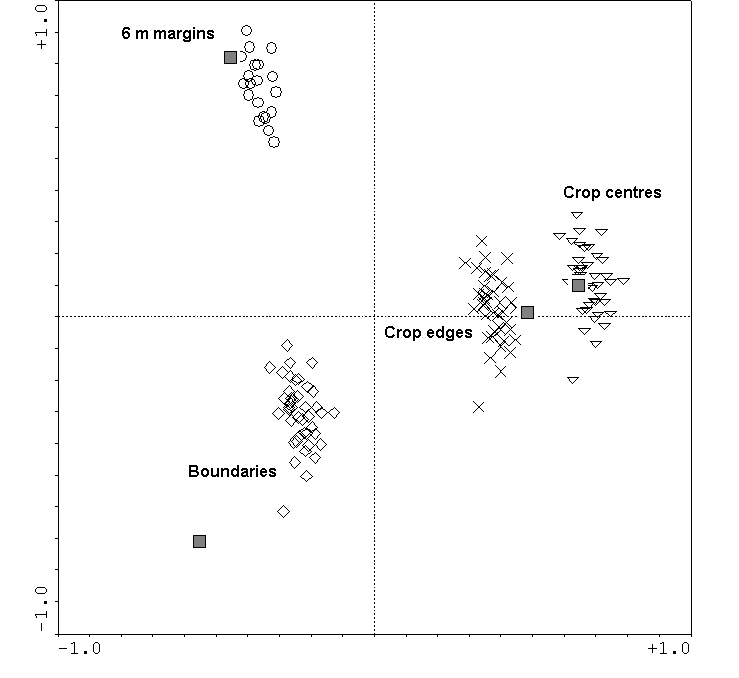
**TABLE 1** Mean values of land cover and farm inputs for field sites in three landscape types. NS = not significant

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | 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**