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Contact CEH NORA team at
noraceh@ceh.ac.uk

1   Cereal density and N-fertiliser effects on the flora and biodiversity value of arable headlands

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3   Markus Wagner*, James, M. Bullock, Lucy Hulmes, Sarah Hulmes, Richard F. Pywell

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5   NERC Centre for Ecology & Hydrology, Benson Lane, Wallingford, Oxfordshire OX10 8BB, UK

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7   *Corresponding author (email: mwagner@ceh.ac.uk

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27   Abstract:

28   Modern intensive farming caused pronounced changes to the European arable flora. Many species

29   adapted to less intensive traditional farming declined severely, as did the potential of unsown arable

30   vegetation to support higher trophic levels. To reverse these trends, various agri-environment

31   measures were introduced. One such measure is to manage cereal headlands as conservation

32   headlands, involving strict restrictions on pesticide and fertiliser use. An additional modification to

33   management which could reduce crop competition and thus deliver benefits to arable plants is

34   cereal sowing at reduced rates. However, little is known about its benefits to rare and declining

35   arable plants, or to species of value to higher trophic levels, and whether it can be implemented

36   without concomitant increase in undesirable weeds.

37   We set up identical two-factorial experiments in winter wheat and spring barley, combining a

38   nitrogen fertiliser vs. no fertiliser treatment with cereal sowing at economic rates vs. sowing at rates

39   reduced by 75%, with added sowing of a mixture of rare arable species. Both experiments also

40   included an uncropped but cultivated control equivalent to another agri-environment measure.

41   Our results show that reduced cereal sowing in conservation headlands can benefit rare and

42   declining species, as well as arable plant diversity, without necessarily resulting in a concomitant

43   increase in undesirable weeds. While such benefits tended to be larger in uncropped cultivated

44   controls, conservation headlands have the advantage of not requiring land being taken out of

45   production. Moreover, as shown in this study, their benefits to arable plants can be maximised by

46   reduced sowing.

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50   Keywords: agri-environment schemes; agro-ecology; conservation headlands; crop competition; rare

51   arable plants; weed management

52

53   Introduction

54   From the late 1940s onwards, intensive methods of arable farming were rapidly adopted both in the

55   UK (Robinson and Sutherland 2002) and in continental Europe (Stoate et al. 2001). Continued

56   mechanisation, along with a substantial increase in the use of herbicides and fertilisers, facilitated a

57   shift away from traditional mixed arable and livestock farming practices. These changes included a

58   move towards simplified crop rotations which no longer included fallow periods, a shift from spring-

59   sown to autumn-sown cereals (Stoate et al. 2001; Robinson and Sutherland 2002), and a shift from

60   ploughing to non-inversion tillage (Chancellor et al. 1984; Cannell 1985; Morris et al. 2010). These in-

61   field changes were accompanied by a reduction in non-productive landscape features and a trend of

62   increasing farm size (Stoate et al. 2001; Robinson and Sutherland 2002).

63   In their entirety, these developments had profound effects on the non-crop arable flora.

64   Many non-crop species characteristic of traditional arable management declined dramatically, both

65   in the UK (Sutcliffe and Kay 2000; Potts et al. 2010) and across Europe (Hilbig and Bachthaler 1992a,

66   Richner et al. 2015), and trait-based analyses (Storkey et al. 2010; Pinke and Gunton 2014) have

67   provided insights in the underlying mechanisms of decline. At the same time, other species

68   benefited from arable intensification, e.g. through their abilities to evolve herbicide resistance, to

69   efficiently exploit high levels of nutrient availability, and to fit in with simplified cultivation and

70   cropping regimes (Froud-Williams et al. 1983; Hilbig and Bachthaler 1992b; Hald 1999; Sutcliffe and

71   Kay 2000), many of them becoming weeds. The net result of arable intensification was a steep

72   decline in overall abundance and species diversity of non-crop plants, both in the UK (Sutcliffe and

73   Kay 2000; Potts et al. 2010) and across Europe (Richner et al. 2015; Albrecht et al. in press). This is

74   not only relevant in terms of the arable flora *per se*, with many traditional non-crop arable species

75   now being threatened (Albrecht et al. in press), but also because of the important role that non-crop

76   arable plants play as a food resource for higher trophic levels, including pollinating insects, other

77   farmland invertebrates, and farmland birds (Wilson et al. 1999; Marshall et al. 2003; Franke et al.

78   2009; Bretagnolle and Gaba 2015). This role has also been demonstrated experimentally in studies

79   showing that rigorous weed control adversely affects such higher trophic levels (Hawes et al. 2003).

80   The potential benefits of restrictions on agrochemical inputs into cropped field margins to

81   arable plant diversity in general and to rare and threatened species in particular have been

82   recognized since experiments investigating the benefits of reducing pesticide inputs to field

83   headlands were done in the late 1970s and early 1980s, e.g. in Germany (Schumacher 1980) and in

84   the UK (Boatman and Wilson 1988; Sotherton 1990). Similar experiments were subsequently carried

85   out in Sweden (Chiverton 1994; Fischer and Milberg 1997) and in the Netherlands (de Snoo 1995;

86   Kleijn and van der Voort 1997).

87   In England, in response to the findings of these early studies, conservation headlands were

88   first made available as agri-environment scheme (AES) options as part of the Arable Stewardship

89   Pilot Scheme launched in two regions in 1998 (MAFF 1998). In 2002, these options were extended

90   nationwide as part of the Countryside Stewardship Scheme (Defra 2002). In both schemes, two kinds

91   of cereal headland option were offered, both with similar restrictions on herbicide use, and one with

92   an additional ban on fertiliser application. Assessments of both schemes indicated that non-fertilised

93   conservation headlands tended to be characterised by higher non-crop plant cover and species

94   richness than their fertilised counterparts (Critchley et al. 2004; Walker et al. 2007). However,

95   compared to uncropped cultivated margins, another arable AES option designed to promote arable

96   plants, conservation headlands, even when unfertilised, tended to deliver relatively small benefits

97   for arable plant diversity and rare arable species, when compared against conventionally-managed

98   cereal margins with no restrictions on agrochemical or fertiliser inputs (Critchley et al. 2004; Walker

99   et al. 2007).

100   One further potential modification to the management of cereal headlands that might

101   positively affect the size of benefit to arable biodiversity offered by conservation headlands is

102   reduction in cereal sowing density, which is currently not promoted by the AES in Britain. Growth of

103   uncompetitive rare arable species in cereal stands is positively related to light penetration levels,

104 and these levels continuously decline while cereals grow, and form an increasingly dense canopy.

105 Accordingly, the primary reason why rare arable weed species perform better in unfertilised cereal

106 stands than in fertilised ones appears to be that a decline to critical threshold light penetration levels

107 below which growth of rare arable species is restricted may occur more rapidly in fertilised stands,

108 resulting in a reduced temporal window for growth of these species (Kleijn and van der Voort 1997).

109 By potentially extending this temporal window, reduced cereal sowing densities may promote both

110 rare as well as more common arable species. On the other hand, sowing of cereal at reduced

111 densities means that more resources become available to individual cereal plants, and we do not

112 know to what extent increased tillering (Kirby 1967; Champion et al. 1998), particularly at high levels

113 of nutrient availability (Aspinall 1961), may counteract the effects of reduced sowing, and thus limit

114 any expected benefit to rare arable species. Moreover, if such benefits can be achieved, it is

115 important that they can be delivered without simultaneously boosting populations of agronomically

116 undesirable species, i.e. weeds (Jones and Smith 2007). This is even more important given farmers'

117 concerns regarding potential infestations by such undesirable weeds (Still and Byfield 2007), which

118 may in fact be at least partly responsible for the low uptake of UK AES options targeted at boosting

119 rare arable plants (Clothier 2013).

120 Sowing cereals at reduced density has also recently been advocated in the context of

121 reintroducing rare species by means of sowing (Epperlein et al. 2014). In many instances, such active

122 reintroduction may be required, as natural recolonization may be highly unlikely, due to the fact that

123 after extended periods of intensive management, rare species often are also no longer present in

124 the local soil seed bank after having been lost from the vegetation, and due to many rare species

125 lacking adaptations for dispersal (Albrecht et al. in press). A recent field study by Lang et al. (2016)

126 showed that rare arable species can be reintroduced into cereal crops, provided the crop is managed

127 sympathetically with respect to the needs of these species. Results from such studies also indicate

128 that, as expected, yield losses due to reintroduction of uncompetitive rare species tend to be

129 negligible (Epperlein et al. 2014; Lang et al. 2016).

130   High rates of establishment in the first year after reintroduction may be crucial for long-term

131   persistence, and at the same time would help bring down the cost of sowing rare species, which can

132   be significant, given that few such species are as yet commercially available (Albrecht et al. in press).

133   Nonetheless, few studies have so far investigated whether using reduced cereal sowing rates could

134   boost rare species establishment (but see Albrecht et al. 2014).

135   Furthermore, previous studies investigating the effects of reduced cereal sowing density

136   have tended to ignore the potential effects of such a practice on species beneficial to arable faunal

137   biodiversity and on agronomically undesirable species. In particular the latter aspect is important

138   with respect to farmers' acceptance of reduced sowing rates in cereal headlands to deliver benefits

139   for biodiversity.

140   In this study, we use experimental manipulation in conventionally-managed cereal fields to address

141   the following questions:

142   (1) How do sowing rate of major winter and spring cereal crops and application of nitrogen fertiliser

143   affect species richness and overall abundance of desirable and undesirable arable plant species in

144   arable headlands managed for conservation?

145   (2) What are the effects on establishment of sown rare arable species?

146   (3) In terms of impacts on the arable flora, how do experimental cereal headlands compare with

147   field margins managed as uncropped cultivated land?

148

149   Materials and Methods

150   Experimental design

151   Our study was carried out at Roundwood Estate, in the Hampshire Downs, England (51°12'N,

152   1°17'W), in a typical arable landscape characterised by large arable fields with scattered woodland

153   blocks and low hedgerows, with free-draining, thin chalky loams being the predominant soil type

154   (Natural England 2014). A survey of arable plants carried out in 2009 confirmed a rich arable flora

155   containing a large number of rare and declining arable species (Wilson 2010), making the estate a

156 site of international importance for its arable flora according to Plantlife's Important Arable Plant

157 Area (IAPA) system (Byfield and Wilson 2005). Preliminary inspection of fields revealed low

158 abundances of undesirable weed species, indicating high suitability for AES measures aimed at

159 boosting rare and declining arable species.

160 To determine the effects of cereal sowing density and of N fertilisation on arable plant

161 species in cereal headlands, separate randomised block experiments were set up in different fields

162 for winter wheat and for spring barley. Accordingly, in the following, these experiments will be

163 referred to as the winter wheat experiment and the spring barley experiment. Both experiments

164 were set up along headlands 12 m wide, and each experiment consisted of four replicate blocks with

165 five treatments. Of these treatments, four corresponded to a 2x2 factorial design, with the two

166 factors being cereal sowing density (sown at a standard density falling within the range of

167 recommended densities for achieving optimum yield vs sown at 25% of this standard density) and N

168 fertilisation (liquid N fertiliser applied at rates typically used for these two respective crops on this

169 type of soil vs no N fertiliser). As shown by crop trials, compared to sowing at a standard density,

170 sowing at 25% of that density can be carried out with minimal yield loss, provided timely sowing is

171 ensured (Kirby 1967; Spink et al. 2000). The fifth treatment was an uncropped control with no cereal

172 sowing and no fertilisation conforming to the cultivated, uncropped field margin management

173 prescription of the English agri-environment scheme. The length of experimental plots was 10 m for

174 treatments not receiving N fertiliser, and, due to operational requirements for fertiliser spreading,

175 20 m for treatments receiving N fertiliser.

176 In the winter wheat experiment, on 27 September 2013, seeds of winter wheat var. Horatio were

177 drilled to a depth of 2.5 cm, using rates of 320 seeds m^{-2} and of 80 seeds m^{-2}, respectively, on

178 standard-density and quarter-density plots. In the spring barley experiment, on 14 March 2014,

179 spring barley var. Concerto was drilled to a depth of 2.5 cm, using rates of 350 seeds m^{-2} and of 88

180 seeds m^{-2}, respectively, on standard-density and quarter-density plots.

181   Pre-drilling, all treatment plots were cultivated using a Knight triple press, and phosphorus

182   and potassium fertiliser was applied at fixed rates of 50 kg P ha^{-1} and 60 kg K ha^{-1}. On the same day

183   as the cereals were drilled, seed mixtures containing five rare arable annual species – *Kickxia spuria*,

184   *Lithospermum arvense*, *Papaver argemone*, *Scandix pecten-veneris*, and *Silene noctiflora*

185   (nomenclature follows Stace 2010) – were sown into the central 5 m × 5 m area of each plot. Sowing

186   rates varied among species, ranging between 30 seeds m^{-2} for the largest-seeded species, *S. pecten-*

187   *veneris*, and 285 seeds m^{-2} for the smallest-seeded species, *P. argemone*, with the remaining species

188   sown at 150 seeds m^{-2}. A similar rationale, based on the assumption of a positive correlation

189   between seed size and establishment probability, has also been applied by e.g. Lang et al (2016). All

190   of these species have been reported to occur at the estate, albeit generally only locally and at low

191   densities (Wilson 2010). Liquid fertiliser was applied to the growing cereal crop to treatment plots

192   designated to receive N fertiliser, at rates of 240 kg ha^{-1} N and 48 kg ha^{-1} S to winter wheat, and of

193   130 kg ha^{-1} N and 22 kg ha^{-1} S to spring barley respectively, in line with regular practice at the estate

194   when growing these crops.

195

196   Data collection

197   A single count of all sown rare arable species, combined with a vegetation survey of all arable plants,

198   was carried out between 28 July and 30 July 2014, just before the harvest of winter wheat and spring

199   barley. Recording was carried out in the central 5 m × 5m area of each treatment plot in five 0.5 m ×

200   0.5 m quadrats that were placed in a regular pattern, one in the centre of the plot, and the other

201   four in the centres of each of four 2.5 m x 2.5 quadrants.

202   In each quadrat, the following parameters were recorded: (1) numbers of individuals of each sown

203   species; (2) total number of cereal tillers; (3) vegetation height, using the drop disc method (Stewart

204   et al. 2001); and (4) vegetation composition, by estimating percent visual cover of all species rooting

205   in the quadrat and of bare ground.

206

207   Species classification

208   The herbaceous non-crop species encountered during vegetation recording were classified into four

209   mutually exclusive groups: (1) common species that are of potential value to the fauna of arable

210   habitats and that are not considered undesirable by farmers; (2) common species considered

211   undesirable, irrespective of their potential value to the fauna; (3) specifically arable species that are

212   rare and/or declining, irrespective of their potential value to the fauna; and (4) common species

213   thought to be of only limited benefit to the fauna and that are not considered undesirable

214   (= 'neutral' species). Regarding the group of undesirable species, we mostly followed the list of

215   common pernicious weeds by Storkey and Westbury (2007), but added two competitive species

216   encountered in our experiments, *Dactylis glomerata* and *Urtica dioica*. Some of the species

217   considered undesirable – in particular *Cirsium arvense*, *Cirsium vulgare*, *Rumex crispus*, *Senecio*

218   *jacobaea*, and *Urtica dioica* – can deliver considerable potential benefit to farmland birds and

219   invertebrates. Nonetheless, for two reasons, a classification into mutually exclusive groups appeared

220   preferable over assigning these species to multiple groups. Firstly, as the aforementioned species

221   are tall-growing and do not flower in the first year after establishment, any benefits specifically to

222   pollinating insects (via nectar and pollen) and to farmland birds (mostly via seeds) are highly unlikely

223   to materialize within a single year after cereal sowing, even in the case of overwintering stubble.

224   Secondly, as this study is concerned specifically with the management of arable headlands in

225   keeping with AES options whose uptake by the farming community is noticeably affected by farmers'

226   concerns over infestations by undesirable weeds (Clothier 2013), it appeared expedient to focus

227   specifically on the potential benefits to arable fauna brought about by those species other than

228   undesirable weeds.

229   Regarding the plant species potentially benefitting faunal biodiversity, we considered three

230   different aspects of potential value: (1) to phytophagous insects; (2) to farmland birds; and (3) to

231   insect pollinators. Value to phytophagous insects was assessed on the basis of numbers of unique

232   species-level interactions in the Database of British Insects and their Foodplants (DBIF; available

233   online at http://www.brc.ac.uk/dbif/ and accessed on 8 April 2016; see Smith and Roy 2008). Value

234   to farmland birds was assessed at the genus level, based on information in the review by Holland et

235   al. (2006). Value to insect pollinators was primarily assessed on the basis of a recently published

236   nectar database (Baude et al. 2016), under additional consideration of a plant species' ability to

237   provide nutritionally valuable pollen collected by insect pollinators, based on the literature (Carvell

238   et al. 2006; Hanley et al. 2008; Kleijn and Raemakers 2008). Rare and declining species were

239   identified on the basis of their IAPA score according to Byfield and Wilson (2005), including all

240   species that had received a rating on the scale from 1 (= of local concern) to 9 (= critically

241   endangered according to Cheffings and Farrell 2005).

242   Results of the classification of 61 non-crop herbaceous species encountered in the winter wheat and

243   spring barley experiments are summarised in Table 1. For a more detailed description of

244   classification criteria and species-level ratings see Table S1. While these ratings suggest that none of

245   the species classified as rare or declining are of notable benefit to faunal biodiversity. This may, to

246   some extent, reflect the paucity of evidence available for rarer species, as e.g. numbers of

247   interactions in the DBIF tend to be positively correlated with the commonness of species (Smith and

248   Roy 2008).

249

250   Statistical analyses

251   Prior to analyses, count data was summed up at plot level across the five sampled 0.5 m × 0.5 m

252   quadrats, and cover and vegetation height data was averaged. Average cover values were arcsine-

253   transformed (Crawley 2007). Average vegetation height was Box-Cox-transformed, with optimal

254   coefficients for transformation being estimated using spread-level plots as provided in the 'car'

255   package v 2.0-12 (Fox and Weisberg 2011) within R v 2.15.1 (R Foundation for Statistical Computing,

256   Vienna, Austria).

257   Disregarding the control treatment, both experiments conformed to a two-factorial design of cereal

258   sowing density vs. nitrogen fertiliser application. Accordingly, we analysed data from each

259   experiment in two ways, (1) as two-factorial design including only treatments involving cereal

260   sowing, and (2) as one-way design including the uncropped cultivated control treatment. For two-

261   factorial analyses, cereal sowing density and nitrogen fertiliser application, along with their two-way

262   interaction, were specified as fixed factors, and block was included as random effect. For one-way

263   analyses, treatment, consisting of five levels, was specified as the sole fixed factor, and block as a

264   random effect. In one-way analyses, in case of a significant treatment effect, pairwise comparisons

265   were carried out using Dunnett tests with Dunnett-Hsu adjustment to investigate differences

266   between the control treatment and each of the four other treatments.

267   Depending on the type of data, one of two kinds of statistical model was used. Total cover of all

268   non-crop vegetation, summed cover of undesirable species, summed cover of species beneficial for

269   faunal biodiversity, summed cover of rare and declining species, vegetation height and bare ground

270   cover were analysed with linear mixed models (LMM), using Proc Mixed in SAS 9.3 for Windows

271   (SAS Institute Inc., Cary, NC, USA). In contrast, count parameters – including cereal tiller density,

272   total species richness, richness of rare and declining species with an IAPA score ≥ 1, and numbers of

273   established plants of sown rare arable species – were analysed with generalized linear mixed models

274   (GLMM) and Poisson errors, using Proc GLIMMIX in SAS 9.3 for Windows (SAS Institute Inc., Cary, NC,

275   USA). Regarding the numbers of established plants of sown species, analyses were carried out for

276   aggregate numbers of plants across all sown species, and individually for those species for which

277   establishment was sufficiently high for allowing successful convergence of the iterative GLMM

278   modelling approach.

279

280   Results

281   Detailed results of two-factorial analyses of the effects of N fertilisation and cereal sowing density

282   are presented in Table S2, with significant results presented below. Results of one-factorial analyses

283   are indicated by asterisks in Figures 1 to 4, showing which individual cereal headland treatments

284   differ significantly from uncropped controls.

285

286   Summed cover and species richness

287   N fertilisation had a negative effect on summed cover of arable plant species in the spring barley

288   experiment ($F_{1,9}$ = 5.24; p = 0.048; see trend in Fig. 1b), but not in the winter wheat experiment

289   (Table S2). However, negative effects of fertilisation on arable plant species richness were manifest

290   in both experiments, but were more pronounced in spring barley ($F_{1,9}$ = 40.59; p < 0.001; see trend in

291   Fig. 2b) than in winter wheat ($F_{1,9}$ = 11.54; p = 0.008; see trend in Fig. 2a). For spring barley, there

292   was a significant interaction with sowing density ($F_{1,9}$ = 9.04; p = 0.015), in that the negative effect of

293   fertilisation was more pronounced at the standard rate of sowing than at the reduced rate (see

294   trend in Fig. 2b). In contrast, in winter wheat, sowing density affected species richness

295   independently of fertiliser application, as indicated by a significant main effect ($F_{1,9}$ = 5.52; p =

296   0.043), with slightly higher richness at reduced sowing density (see trend in Fig. 2a).

297   No significant treatment effects were detected regarding summed cover of species of faunal

298   value (Table S2). However, in spring barley, species richness of this group was highly significantly

299   affected by N fertilisation ($F_{1,9}$ = 14.99; p = 0.004), with a significant interaction ($F_{1,9}$ = 5.85; p = 0.039)

300   indicating that that this effect was more pronounced at the standard rate of sowing than at the

301   reduced rate (see trend in Fig. 2d). In contrast, in winter wheat, N fertilisation fell short of affecting

302   species richness of this group ($F_{1,9}$ = 5.10; p = 0.050).

303   In winter wheat, rare and declining arable species benefited from reduced cereal sowing

304   rates both in terms of summed cover ($F_{1,9}$ = 5.64; p = 0.042; see trend in Fig. 1e) as well as species

305   richness ($F_{1,9}$ = 10.21; p = 0.011; Fig. see trend in 2e), whereas in spring barley, such an effect was

306   only observed for rare species richness ($F_{1,9}$ = 6.89; p = 0.028; see trend in Fig. 2f). N application, on

307   the other hand, had a strong negative effect on rare species in spring barley, both in terms of their

308   summed cover ($F_{1,9}$ = 11.71; p = 0.008; see trend in Fig. 1f) and species richness ($F_{1,9}$ = 14.08; p =

309   0.004; see trend in Fig. 2f), but had no significant effect on either parameter in winter wheat.

310   Summed cover of undesirable weeds was very low in both experiments, and was not

311   significantly affected by experimental treatments regardless of cereal sown (Table S2; see also Figs.

312   1g and 1h).

313

314   Establishment of sown rare species

315   Numbers of established plants pooled across sown species were not affected by the experimental

316   treatments in winter wheat (Table S2), where establishment was generally low. However, in spring

317   barley, where overall establishment was somewhat higher, a significant negative effect of N

318   application was found ($F_{1,9}$ = 9.14; p = 0.014; see trend in Fig. 3b). For individual species,

319   establishment was generally poor, with the exception of *Kickxia spuria*, whose plants made up about

320   2/3 of all recorded individuals (226 out of a total of 343). However, no significant treatment effects

321   were found for this species (Table S2). *Papaver argemone* was characterised by sporadic

322   establishment, with higher establishment in the spring barley experiment, and the three remaining

323   species, *Scandix pecten-veneris*, *Silene noctiflora* and *Lithospermum arvense,* had very low

324   establishment. For all four species, establishment was too low to allow statistical analysis. For a

325   more detailed breakdown of establishment at species level see Table S3.

326

327   Vegetation structure

328   Effects of experimental treatments on bare ground cover were only observed in the winter wheat

329   experiment, where levels were strongly reduced by N fertilisation ($F_{1,9}$ = 18.36; p = 0.002; see trend

330   in Fig. 4a). Effects of cereal sowing rate on wheat tiller density were still detectable just before

331   harvest, i.e. lower tiller densities were observed in plots sown at the reduced rate ($F_{1,9}$ = 20.13; p =

332   0.002). In contrast, no such differences were detectable in spring barley ($F_{1,9}$ = 0.09; p = 0.769). N

333   application, on the other hand, had a much more pronounced effect on tiller density in spring barley

334   ($F_{1,9}$ = 16.15; p = 0.003; see trend in Fig. 4d) than in winter wheat ($F_{1,9}$ = 5.48; p = 0.044; see trend in

335   Fig. 4c). Vegetation height was strongly increased in both crops by N application (winter wheat: $F_{1,9}$ =

336   37.77; p < 0.001; spring barley: $F_{1,9}$ = 348.60; p < 0.001; see trends in Figs. 4e and 4f). Reduction of

337   cereal sowing rate was associated with a small but nonetheless significant increase in vegetation

338   height in spring barley ($F_{1,9}$ = 6.83; p = 0.028; see trend in Fig. 4f).

339

340   Comparison of cereal headland treatments with the uncropped cultivated treatment

341   In the spring barley experiment, summed cover of all arable plant species and of rare and declining

342   species was generally higher in uncropped cultivated control plots than in either of the cereal

343   headland treatments, with significant differences being highlighted in Figs. 1b and 1f. With the

344   exception of the cereal headland treatment involving cereal sowing at the standard rate in the

345   absence of N application, this was also the case for species of faunal value, as highlighted in Fig. 1d.

346   Generally, many fewer significant pairwise differences between the uncropped cultivated treatment

347   and individual cereal headland treatments were found in the winter wheat experiment (left-hand

348   side of Fig. 1), where, compared to the spring barley experiment (right-hand side of Fig. 1), summed

349   cover generally tended to be higher in cereal-sown plots, particularly in the case of arable species in

350   general and of species of faunal value, as shown in the top two rows of Fig. 1.

351   Species richness not just of non-crop species in general, but also of species of faunal value

352   and of rare and declining species, was generally not higher on uncropped cultivated plots than on

353   cereal-sown plots, with the exception of spring barley plots sown at the standard rate and receiving

354   N fertiliser, as highlighted for each respective group in Figs. 2b, 2d, and 2f.

355   Similarly, a comparison of sown species establishment pooled across all sown species,

356   between uncropped cultivated treatment and the cereal headland treatments, yielded only a single

357   pairwise difference between a headland treatment and the uncropped treatment, again for spring

358   barley sown at the standard rate and receiving N fertiliser, as highlighted in Fig. 3b.

359   Structurally, uncropped cultivated control plots differed markedly from cereal headland plots, with

360   vegetation height and, for obvious reasons, cereal tiller density, being markedly lower in the former,

361   as highlighted in Figs. 4c to 4f. On the other hand, as highlighted in Figs. 4a and 4b, levels of bare

362 ground just before harvest tended to be roughly similar between uncropped controls and cereal-

363 sown headland treatments.

364

365 Discussion

366 Conservation headlands involving restrictions to agrochemical and fertiliser inputs have the

367 distinctive advantage of providing ecosystem services and supporting rare and declining arable

368 plants without requiring land being taken out of food production (Albrecht et al. in press). This study

369 shows that reduced rates of cereal sowing in such headlands can help boost extant populations of

370 rare and declining arable species, both in terms of total cover as well as in terms of species richness,

371 without necessarily resulting in a pronounced increase in undesirable weeds, if levels of the latter

372 are low to begin with.

373 These positive effects of a reduction in cereal sowing density on extant rare arable species

374 appeared to be more pronounced in winter wheat. In contrast, fertilisation had pronounced

375 negative effects in spring barley, but not in winter wheat. As evidenced by treatment effects on tiller

376 density, these crop-specific differences in treatment effect on rare species may at least partly have

377 been the result of intrinsic differences between the tested cereals crops in terms of their ability to

378 respond to higher resource availability at the level of individual plants - brought about either by

379 reduced sowing or by added nitrogen - with increased tillering. Such a tillering response was

380 generally more pronounced in the spring barley experiment than in the winter wheat experiment.

381 Unlike the wheat crop, the barley crop compensated perfectly for reduced sowing by increased

382 tillering. Similarly, the tiller density increase in response to N application was more pronounced in

383 barley than in wheat.

384 On the other hand, while the observed differences between cereals in tillering thus appear

385 to support an explanation of crop-specific responses to treatments, seasonal differences in the

386 timing of cultivation between the two crops may have also have contributed to our results. Many

387 rare arable species show seasonal preferences in terms of emergence (Wilson 1994; Pywell et al.

388 2010), and the same applies to common species, resulting in marked effects of cultivation season on

389 floristic composition (Hald 1999; Critchley et al. 2006).

390 Nonetheless, in the case of N fertilisation, similar crop-specific effects on the weed flora to

391 the ones found by us were found by Bischoff and Mahn (2000). In their three-year study on a long-

392 term crop-rotation experiment, peak weed densities were significantly lower on plots receiving N

393 fertiliser than on plots not receiving N in the year when spring barley was planted, whereas in the

394 year when winter wheat was planted, the opposite was the case, indicating that weed densities in

395 spring barley, but not in winter wheat, were suppressed by N application.

396

397 Management for rare and declining species

398 Few insights were possible based on the sowing component of our experiments due to the sporadic

399 establishment of all but one sown rare species, although we found that, pooled across species, in

400 spring barley, establishment was significantly reduced by N application. However, potentially due to

401 this sporadic establishment, we failed to establish any potential effects of reduced cereal sowing

402 density. Recent work by Albrecht et al. (2014) has shown that establishment of rare arable species

403 can indeed be bolstered by sowing cereals at reduced rate, although they tested other cereals in

404 their study, i.e. rye and spelt. The results of previous studies suggest that reduced cereal sowing can

405 also boost size (Svensson and Wigren 1982; Kleijn and van der Voort 1997; Albrecht et al. 2014) and

406 per capita seed production (Peters and Gerowitt 2014) of rare arable plant individuals. In the present

407 study, additional insights regarding the effects of cereal sowing rate on rare and declining species

408 were obtained from analyses of summed cover and species richness of the group of rare and

409 declining arable species found in the experiment, including both unsown and sown species. These

410 analyses demonstrated that reduced cereal sowing rate increased both summed cover and species

411 richness of rare and declining arable species in winter wheat, but only species richness in spring

412 barley.

413   Regarding the effects of N application, in line with the observed reduction in establishment

414   of sown rare species, analyses both of summed cover and species richness of rare and declining

415   species in spring barley also indicated a strong negative effect of N fertilisation. However, no such

416   effects were detected in the winter wheat experiment.

417   Taken together, these findings appear to suggest that N application may affect rare and declining

418   species more strongly in spring barley than in winter wheat. However, it is important to keep in mind

419   that these were two separate experiments carried out in different fields. As indicated by the

420   uncropped control treatments in both experiments, which provide an indication of potential

421   maximum values of summed cover and species richness of rare and declining species as well as of

422   sown species establishment, higher maxima for all three variables occurred in spring barley than in

423   winter wheat. This suggests that it may have been more difficult to detect significant N application

424   effects on rare and declining species in winter wheat than in spring barley. Moreover, negative

425   effects on N application on rare species establishment in winter wheat have been demonstrated by

426   previous studies (e.g. Wilson 1999), and our results should thus not be interpreted as a challenge to

427   the perceived wisdom of N application negatively affecting populations of rare arable species in

428   cereal crops.

429

430   Management for plant and faunal diversity

431   Our study failed to demonstrate evidence from our study for reduced rates of cereal sowing to result

432   in increased cover of common arable species of faunal value that are expected to support higher

433   trophic groups, although reduced sowing of winter wheat resulted in slightly more species-rich

434   arable vegetation, which could mean resource provision for a wider range of fauna (Meek et al.

435   2002; Asteraki et al. 2004).

436   There was however strong evidence for beneficial effects of not applying N fertiliser on non-

437   crop plant diversity, both in terms of overall species richness, as well as in terms of richness of those

438   species known to be of faunal value. Both in the winter wheat experiment and in the spring barley

439   experiment, and in agreement with findings from a comparative study of arable options in a

440   previous English AES (Walker et al. 2007), non-crop species richness was much higher in cereal

441   stands not receiving N fertiliser than in those with N application. The same clearly applied to species

442   of faunal value in spring barley, and a similar effect in winter wheat bordered on significance. Again,

443   such positive treatment effects on plant species richness may be indicative of an increased ability of

444   the plant cover to support higher faunal diversity (Meek et al. 2002; Asteraki et al. 2004). Matching

445   these findings for species richness, N application resulted in reduced summed cover of non-crop

446   species in the spring barley experiment, but not in the winter wheat experiment.

447   In agreement with our findings, Kleijn and van der Voort (1997) demonstrated a clear

448   negative relationship between N application and light penetration beneath the canopy of barley

449   stands, whereas previous studies carried out in wheat crops have shown that N fertilisation can

450   boost both establishment (Bischoff and Mahn 2000) and total biomass of weeds (Rial-Lovera et al.

451   2016). Together with these findings by other authors, our results suggest that effects of N

452   application on the arable flora may vary between different types of cereal, e.g. being potentially

453   more detrimental in spring barley than in winter wheat.

454   Summed cover of species of biodiversity value remained unaffected by N application,

455   irrespective of cereal sown. While, due to comparatively low replication, our ability to detect such

456   effects may have been somewhat limited, our findings indicate that restricting N application does

457   not necessarily lead to marked increases in resource provision to arable fauna. In fact, e.g. in wheat

458   crops, certain potentially beneficial species may respond positively to N fertilisation (Rial-Lovera et

459   al. 2016).

460

461   Comparison of cereal headlands with uncropped cultivated controls

462   In spring barley, summed cover of arable species, as well as of species of faunal value and of rare

463   and declining species, tended to be higher in uncropped cultivated controls treatment than in the

464   various cereal headland treatments. However, no such effects was found for overall species richness

465   or for richness of rare and declining species, except for comparing uncropped controls with the most

466   intensively-managed type of headland which received N fertiliser and was sown at standard density.

467   In contrast, in winter wheat, there were hardly any differences between control plots and the

468   various types of cereal headland treatments, suggesting that cereal exerted much stronger

469   competitive effects on the non-crop vegetation in the spring barley experiment than in the winter

470   wheat experiment. While these results also fit with the observation of higher compensatory tillering

471   in spring barley, providing an explanation in terms of more intense competition, it is again important

472   to keep in mind that timing of cultivation may also have affected species composition, e.g. due to

473   seasonal preferences for emergence.

474

475   Conclusions

476   In this study, we have demonstrated the potential benefits to rare and declining arable species in

477   conservation headlands of reduced cereal sowing densities, and we have confirmed similar benefits

478   from restrictions in N fertiliser application. However, as suggested by the crop-specific results both

479   in the winter wheat and spring barley experiments, the relative extent of such benefits may vary

480   between different types of cereal, e.g. in relation to attributes such as tillering capacity or crop

481   height (Andrew et al. 2015), or e.g. depending on season of sowing. Thus, building on the findings of

482   this study, further experiments investigating these aspects of managing conservation headlands

483   should focus on establishing under which conditions such management modifications may deliver

484   the greatest benefit to rare and declining arable plants.

485

494   References

495   Albrecht H, Cambecèdes J, Lang M, Wagner M (in press) Management options for rare arable plants

496   in Europe. Bot Lett 164(4). doi:10.1080/23818107.2016.1237886

497   Albrecht H, Prestele J, Altenfelder S, Wiesinger K, Kollmann J (2014) New approaches to the

498   conservation of rare arable plants in Germany. In: Nordmeyer H, Ulber L (eds) Delivering arable

499   biodiversity. Proceedings 26th German Conference on Weed Biology and Weed Control

500   March 11-13, 2014, Braunschweig. Bundesforschungsinstitut für Kulturpflanzen, Braunschweig, pp

501   180-189. http://pub.jki.bund.de/index.php/JKA/article/download/2864/3057 Accessed 20 April 2016

502   Andrew IKS, Storkey J, Sparkes DL (2015) A review of the potential for competitive cereal cultivars as

503   a tool in integrated weed management. Weed Res 55:239-248. doi:10.1111/wre.12137

504   Aspinall D (1961) The control of tillering in the barley plant. 1. The pattern of tillering and its relation

505   to nutrient supply. Aus J Biol Sci 14:493-505. doi:10.1071/BI9610493

506   Asteraki EJ, Hart BJ, Ings TC, Manley WJ (2004) Factors influencing the plant and invertebrate

507   diversity of arable field margins. Agr Ecosyst Environ 102:219-231. doi: 10.1016/j.agee.2003.07.003

508   Baude M, Kunin WE, Boatman ND, Conyers S, Davies N, Gillespie MAK, Morton D, Smart SM,

509   Memmott J (2016) Historical nectar assessment reveals the fall and rise of floral resources in Britain.

510   Nature 530:85-88. doi: 10.1038/nature16532

511   Bischoff A, Mahn E-G (2000) The effects of nitrogen and diaspore availability on the regeneration of

512   weed communities following extensification. Agr Ecosyst Environ 77:237-246. doi:10.1016/S0167-

513   8809(99)00104-8

514   Boatman ND, Wilson PJ (1988) Field edge management for game and wildlife conservation. In: The

515   practice of weed control and vegetation management in forestry, amenity and conservation areas.

516   Aspects of Applied Biology, Vol. 16. Association of Applied Biologists, Wellesbourne, pp 89-94

517   Bretagnolle V, Gaba S (2015) Weeds for bees? A review. Agron Sustain Dev 35:891-909. doi:

518   10.1007/s13593-015-0302-5

519   Byfield AJ, Wilson PJ (2005) Important Arable Plant Areas: identifying priority sites for arable plant

520   conservation in the United Kingdom. Plantlife International, Salisbury.

521   http://www.plantlife.org.uk/uploads/documents/Important_Arable_Plant_Areas.pdf. Accessed 20

522   April 2016

523   Cannell RQ (1985) Reduced tillage in north-west Europe – a review. Soil Till Res 5:129-177.

524   doi:10.1016/0167-1987(85)90028-5

525   Carvell C, Westrich P, Meek WR, Pywell RF, Nowakowski M (2006) Assessing the value of annual and

526   perennial forage mixtures for bumblebees by direct observation and pollen analysis. Apidologie

527   37:326-340. doi:10.1051/apido:2006002

528   Champion GT, Froud-Williams RJ, Holland JM (1998) Interactions between wheat (Triticum aestivum

529   L.) cultivar, row spacing and density and the effect on weed suppression and crop yield. Ann Appl

530   Biol 133:443-453. doi:10.1111/j.1744-7348.1998.tb05842.x

531   Chancellor RJ, Fryer JD, Cussans GW (1984) The effects of agricultural practices on weeds in arable

532   land. In: Jenkins D (ed) Agriculture and the environment - proceedings of ITE symposium no. 13 held

533   at Monks Wood Experimental Station on 28-29 February and 1 March 1984. Institute of Terrestrial

534   Ecology, Cambridge, pp 89-94

535   Cheffings CM, Farrell L (2005) The vascular plant Red Data List for Great Britain. Species Status No. 7.

536   Joint Nature Conservation Committee, Peterborough.

537   Chiverton PA (1994) Large-scale field trials with conservation headlands in Sweden. In: Boatman N

538   (ed) Field margins: integrating agriculture and conservation. BCPC Monograph No. 58. British Crop

539   Production Council, Farnham, pp 89-94

540   Clothier L (2013) Campaign for the Farmed Environment: Entry Level Stewardship option uptake.

541   Defra Agricultural Change and Environment Observatory Research Report No. 32. Department for

542   Environment, Food and Rural Affairs, London.

543   https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/183937/defra-

544   stats-foodfarm-environ-obs-research-setaside-farmenviroment-ELSinCFEjan13-130214.pdf. Accessed

545   20 April 2016

546   Crawley MJ (2007) The R book. Wiley, Chichester.

547   Critchley CNR, Allen DS, Fowbert JA, Mole AC, Gundrey AL (2004) Habitat establishment on arable

548   land: assessment of an agri-environment scheme in England, UK. Biol Conserv 119:429-442.

549   doi:10.1016/j.biocon.2004.01.004

550   Critchley CNR, Fowbert JA, Sherwood AJ (2006) The effects of annual cultivation on plant community

551   composition of uncropped arable field boundary strips. Agr Ecosyst Environ 113:196-205.

552   doi:10.1016/j.agee.2005.05.013

553   de Snoo GR (1995) Unsprayed field margins: implications for environment, biodiversity and

554   agricultural practice. PhD thesis, University of Leiden.

555   Defra (2002) The Countryside Stewardship Scheme. New arable options from 2002. Department for

556   Environment, Food and Rural Affairs, London.

557   Epperlein LRF, Prestele JW, Albrecht H, Kollmann J (2014) reintroduction of a rare arable weed:

558   competition effects on weed fitness and crop yield. Agr Ecosyst Environ 188:57-62.

559   doi:10.1016/j.agee.2014.02.011

560   Fischer A, Milberg P (1997) Effects on the flora of extensified use of field margins. Swed J Agr Res

561   27:105-111

562   Fox J, Weisberg S (2011) An R companion to applied regression, 2nd edn. Sage Press, Thousand Oaks

563   Franke AC, Lotz LAP, van der Burg WJ, van Overbeek L (2009) The role of arable weed seeds for

564   agroecosystem functioning. Weed Res 49:131-141. doi:10.1111/j.1365-3180.2009.00692.x

565   Froud-Williams RJ, Drennan DSH, Chancellor RJ (1983) Influence of cultivation regime on weed floras

566   of arable cropping systems. J Appl Ecol 20:187-197. doi:10.2307/2403385

567   Hald AB (1999) The impact of changing the season in which the cereals are sown on the diversity of

568   the weed flora in rotational fields in Denmark. J Appl Ecol 36:24-32. doi:10.1046/j.1365-

569   2664.1999.00364.x

570   Hanley ME, Franco M, Pichon S, Darvill B, Goulson D (2008) Breeding system, pollinator choice and

571   variation in pollen quality in British herbaceous plants. Funct Ecol 22:592-598. doi:10.1111/j.1365-

572   2435.2008.01415.x

573   Hawes C, Haughton AJ, Osborne JL, Roy DB, Clark SJ, Perry JN, Rothery P, Bohan DA, Brooks DR,

574   Champion GT, Dewar AM, Heard MS, Woiwod IP, Daniels RE, Young MW, Parish AM, Scott RJ,

575   Firbank LG, Squire GR (2003) Responses of plants and invertebrate trophic groups to contrasting

576   herbicide regimes in the Farm Scale Evaluations of genetically modified herbicide–tolerant crops.

577   Philos T Roy Soc B 358:1899-1913. doi:10.1098/rstb.2003.1406

578   Hilbig W, Bachthaler G (1992a) Wirtschaftsbedingte Veränderungen der Segetalvegetation in

579   Deutschland im Zeitraum von 1950-1990. I: Entwicklung der Aufnahmeverfahren, Verschwinden der

580   Saatunkräuter, Rückgang von Kalkzeigem, Säurezeigern, Feuchtezeigern, Zwiebel- und

581   Knollengeophyten, Abnahme der Artenzahlen. Angew Bot 66:192-200

582   Hilbig W, Bachthaler G (1992b) Wirtschaftsbedingte Veränderungen der Segetalvegetation in

583   Deutschland im Zeitraum von 1950-1990. II: Zunahme herbizidverträglicher Arten, nitrophiler Arten,

584   von Ungräsern, vermehrtes Auftreten von Rhizom- und Wurzelunkkräutern, Auftreten und

585   Ausbreitung von Neophyten, Förderung gefährdeter Ackerwildkkrautarten, Integrierter Pflanzenbau.

586   Angew Bot 66:201-209

587   Holland JM, Hutchison MAS, Smith B, Aebischer NJ (2006) A review of invertebrates and seed-

588   bearing plants as food for farmland birds in Europe. Ann Appl Biol 148:49-71. doi:10.1111/j.1744-

589   7348.2006.00039.x

590   Jones NE, Smith BM (2007) Effects of selective herbicide treatment, row width and spring cultivation

591   on weed and arthropod communities in winter wheat. In: Boatman N, Bradbury R, Critchley N,

592   Holland J, Marshall J, Ogilvy S (eds) Delivering arable biodiversity. Aspects of Applied Biology, Vol. 81.

593   Association of Applied Biologists, Wellesbourne, pp 39-46

594   Kirby EJM (1967) The effect of plant density upon the growth and yield of barley. J Agr Sci 68:317-

595   324. doi:10.1017/S0021859600012806

596   Kleijn D, Raemakers I (2008) A retrospective analysis of pollen host plant use by stable and declining

597   bumblebees. Ecology 89:1811-1823. doi:10.1890/07-1275.1

598   Kleijn D, van der Voort LAC (1997) Conservation headlands for rare arable weeds: the effects of

599   fertilizer application and light penetration on plant growth. Biol Conserv 81:57-67.

600   doi:10.1016/S0006-3207(96)00153-X

601   Lang M, Prestele J, Fischer C, Kollmann J, Albrecht H (in press) Re-introduction of rare arable plants

602   by seed transfer. What are the optimal sowing rates? Ecol Evol 6:5506-5516. doi:10.1002/ece3.2303

603   MAFF (1998) The Countryside Stewardship Scheme. Arable Stewardship. Information and How to

604   Apply. Ministry of Agriculture, Fisheries and Food, London.

605   Marshall EJP, Brown VK, Boatman ND, Lutman PJW, Squire GR, Ward LK (2003) The role of weeds in

606   supporting biological diversity within crop fields. Weed Res 43:77-89. doi:10.1046/j.1365-

607   3180.2003.00326.x

608   Meek B, Loxton D, Sparks T, Pywell R, Pickett H, Nowakowski M (2002) The effect of arable field

609   margin composition on invertebrate biodiversity. Biol Conserv 106:259-271. doi:10.1016/S0006-

610   3207(01)00252-X

611   Morris NL, Miller PCH, Orson JH, Froud-Williams RJ (2010) The adoption of non-inversion tillage

612   systems in the United Kingdom and the agronomic impact on soil, crops and the environment – a

613   review. Soil Till Res 108:1-15. doi:10.1016/j.still.2010.03.004

614   Natural England (2014) National Character Area Profile: 130. Hampshire Downs. Natural England

615   Publications. http://publications.naturalengland.org.uk/file/4546775574642688. Accessed 20 April

616   2016

617   Peters K, Gerowitt B (2014) Response of the two rare arable weed species *Lithospermum arvense*

618   and *Scandix pecten-veneris* to climate change conditions. Plant Ecol 215:1013-1023.

619   doi:10.1007/s11258-014-0358-3

620   Pinke G, Gunton RM (2014) Refining rare weed trait syndromes along arable intensification

621   gradients. J Veg Sci 25:978-989. doi:10.1111/jvs.12151

622   Potts GR, Ewald JA, Aebischer NJ (2010) Long-term changes in the flora of the cereal ecosystem on

623   the Sussex Downs, England, focusing on the years 1968-2005. J Appl Ecol 47:215-226.

624   doi:10.1111/j.1365-2664.2009.01742.x

625   Pywell RF, Hulmes L, Meek WR, Nowakowski M (2010) Practical management of scarce arable

626   populations. In: Boatman N, Green M, Holland J, Marshall J, Renwick A, Siriwardena G, Smith B, de

627   Snoo G (eds) Agri-environment schemes – What have they achieved and where do we go from here?

628   Aspects of Applied Biology, Vol. 100. Association of Applied Biologists, Wellesbourne, pp 175-182

629   Rial-Lovera K, Davies WP, Cannon ND, Conway JS (2016) Weed development in spring wheat after

630   contrasting soil tillage and nitrogen treatment. Ann Appl Biol. 169:236-247. doi:10.1111/aab.12294

631   Richner N, Holderegger R, Linder HP, Walter T (2015) Reviewing change in the arable flora of Europe:

632   a meta-analysis. Weed Res 55:1-13. doi:10.1111/wre.12123

633   Robinson RA, Sutherland WJ (2002) Post-war changes in arable farming and biodiversity in Great

634   Britain. J Appl Ecol 39:157-176. doi:10.1046/j.1365-2664.2002.00695.x

635   Schumacher W (1980) Schutz und Erhaltung gefährdeter Ackerwildkräuter durch Integration von

636   landwirtschaftlicher Nutzung und Naturschutz. Natur und Landschaft 55:447-453

637   Smith RM, Roy DB (2008) Revealing the foundations of biodiversity: the Database of British Insects

638   and their Foodplants. Brit Wildlife 20:17-25

639   Sotherton NW (1990) The environmental benefits of conservation headlands in cereal fields.

640   Pesticide Outlook 1:14-18

641   Spink JH, Semere T, Sparkes DL, Whaley JM, Foulkes MJ, Clare RW, Scott RK (2000) Effect of sowing

642   date on the optimum plant density of winter wheat. Ann Appl Biol 137:179-188. doi:10.1111/j.1744-

643   7348.2000.tb00049.x

644   Stace C (2010) New flora of the British Isles, 3rd edn. Cambridge University Press, Cambridge.

645   Stewart KEJ, Bourn NAD, Thomas JA (2001) An evaluation of three quick methods commonly used to

646   assess sward height in ecology. Journal of Applied Ecology 38:1148–1154. doi: DOI: 10.1046/j.1365-

647   2664.2001.00658.x

648   Still K, Byfield A (2007) New priorities for arable plant conservation. Plantlife International, Salisbury.

649   http://www.plantlife.org.uk/uploads/documents/New_Priorities_for_Arable_Plant_Conservation.pd

650   f. Accessed 20 April 2016

651   Stoate C, Boatman ND, Borralho RJ, Rio Carvalho C, De Snoo GR, Eden P (2001) Ecological impacts of

652   arable intensification in Europe. J Environ Manage 63:337-365. doi:10.1006/jema.2001.0473

653   Storkey J (2006) A functional group approach to the management of UK arable weeds to support

654   biological diversity. Weed Res 46:513-522. doi:10.1111/j.1365-3180.2006.00528.x

655   Storkey J, Westbury DB (2007) managing arable weeds for biodiversity. Pest Manag Sci 63:517-523.

656   doi:10.1002/ps.1375

657   Storkey J, Moss SR, Cussans JW (2010) Using assembly theory to explain changes in a weed flora in

658   response to agricultural intensification. Weed Sci 58:39-46. doi:10.1614/WS-09-096.1

659   Sutcliffe OL, Kay QON (2000) Changes in the arable flora of central southern England since the 1960s.

660   Biol Conserv 93:1-8. doi:10.1016/S0006-3207(99)00119-6

661   Svensson R, Wigren M (1982) Några ogräsarters tillbakagång belyst genom konkurrens-, gödslings-

662   och herbicidförsök. Sven Bot Tidskr 76:241-258

663   Walker KJ, Critchley CNR, Sherwood AJ, Large R, Nuttall P, Hulmes S, Rose R, Mountford JO (2007)

664   The conservation of arable plants on cereal field margins: an assessment of new agri-environment

665   scheme options in England, UK. Biol Conserv 136:260-270. doi:10.1016/j.biocon.2006.11.026

666   Wilson JD, Morris AJ, Arroyo BE, Clark SC, Bradbury RB (1999) A review of the abundance and

667   diversity of invertebrate and plant foods of granivorous birds in northern Europe in relation to

668   agricultural change. Agr Ecosyst Environ 75:13-30. doi:10.1016/S0167-8809(99)00064-X

669   Wilson P (1994) Managing field margins for the conservation of the arable flora. In: Boatman N (ed)

670   Field margins: integrating agriculture and conservation. BCPC Monograph No. 58. British Crop

671   Production Council, Farnham, pp 253-258

672   Wilson PJ (1999) The effect of nitrogen on populations of rare arable plants in Britain. In: Boatman

673   ND (ed) Field margins and buffer zones: ecology, management and policy. Aspects of Applied

674   Biology, Vol. 54. Association of Applied Biologists, Wellesbourne, pp 93-100

675   Wilson PJ (2010) The Roundwood Estate – Rare arable plant survey. Unpublished report

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691 Table 1. Results of the classification of herbaceous non-crop species recorded in the winter wheat

692 and spring barley experiments into (A) common species with known faunal value, (B) common

693 'neutral' species with no or just minor faunal value, (C) rare and declining arable species, and (D)

694 undesirable weed species. For further explanation, see text.

(A) With faunal value	(B) Neutral	(C) Rare and declining	(D) Undesirable weeds
Capsella bursa-pastoris	*Aethusa cynapium*	*Anthemis cotula*	*Alopecurus myosuroides*
Cerastium fontanum	*Anagallis arvensis*	*Chaenorhinum minus*	*Avena fatua*
Chenopodium album	*Arenaria serpyllifolia*	*Euphorbia exigua*	*Cirsium arvense*
Echium vulgare	*Epilobium montanum*	*Fumaria densiflora*	*Cirsium vulgare*
Euphorbia helioscopia	*Epilobium obscurum*	*Fumaria parviflora*	*Dactylis glomerata*
Fumaria officinalis	*Epilobium parviflorum*	*Kickxia elatine*	*Elytrigia repens*
Fallopia convolvulus	*Epilobium tetragonum*	*Kickxia spuria*	*Galium aparine*
Galium verum	*Lapsana communis*	*Lamium amplexicaule*	*Rumex crispus*
Medicago lupulina	*Maricaria discoidea*	*Legousia hybrida*	*Senecio jacobaea*
Myosotis arvensis	*Papaver dubium*	*Papaver argemone*	*Urtica dioica*
Papaver rhoeas	*Plantago major*	*Papaver hybridum*	
Plantago lanceolata	*Sisymbrium officinale*	*Scandix pecten-veneris*	
Poa annua	*Veronica arvensis*	*Sherardia arvensis*	
Poa pratensis	*Veronica persica*	*Silene noctiflora*	
Polygonum aviculare	*Vulpia bromoides*		
Senecio vulgaris			
Silene latifolia			
Sonchus asper			
Stellaria media			
Taraxacum officinale agg.			
Trifolium repens			
Tripleurospermum inodorum			
Viola arvensis			

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701   Figure captions:

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703   Figure 1. Summed percent cover of (a, b) all non-crop species, (c, d) species of faunal value, (e, f)

704   rare and declining arable species, and (g, h) undesirable weeds. Left panel: winter wheat

705   experiment; right panel: spring barley experiment. Back-transformed means ± SE shown for different

706   combinations of cereal sowing at standard ('1/1') vs. one-quarter of standard ('1/4') densities and N

707   application at typical rates ('+N') vs. no N ('-N'), and also for an uncropped cultivated control

708   treatment ('Control'). Asterisks indicate significant pairwise differences between individual cereal-

709   sown treatments and the uncropped control (Dunnett tests: *: $0.01 \leq P < 0.05$; **: $0.001 \leq P < 0.01$'

710   ***: $P < 0.001$).

711

712   Figure 2. Species richness per 1.25 m^2 of (a, b) all non-crop species, (c, d) species of faunal value, and

713   (e, f) rare and declining arable species. Means ± SE shown. See also caption and legend of Fig. 1.

714

715   Figure 3. Establishment of sown rare arable species in terms of numbers of plants per m^2 of (a, b) all

716   sown species pooled together and (c, d) *K. spuria*. Means ± SE shown. See also caption and legend of

717   Fig. 1.

718

719   Figure 4. Vegetation structural parameters, including (a, b) percentage bare ground, (c, d) cereal

720   tiller density, as number of tillers per m^2, and (e, f) vegetation height in metres. Means ± SE shown.

721   See also caption and legend of Fig. 1.

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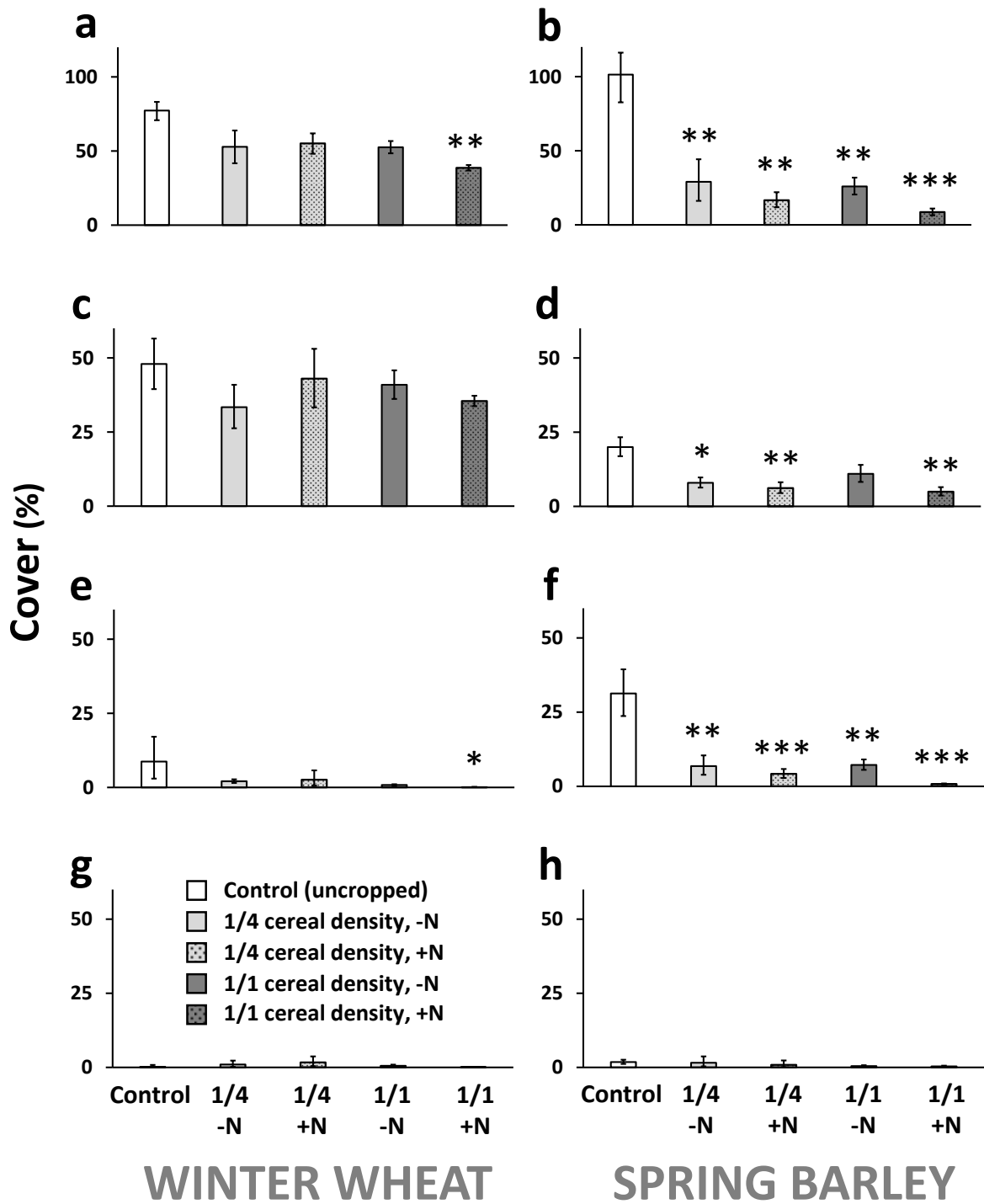
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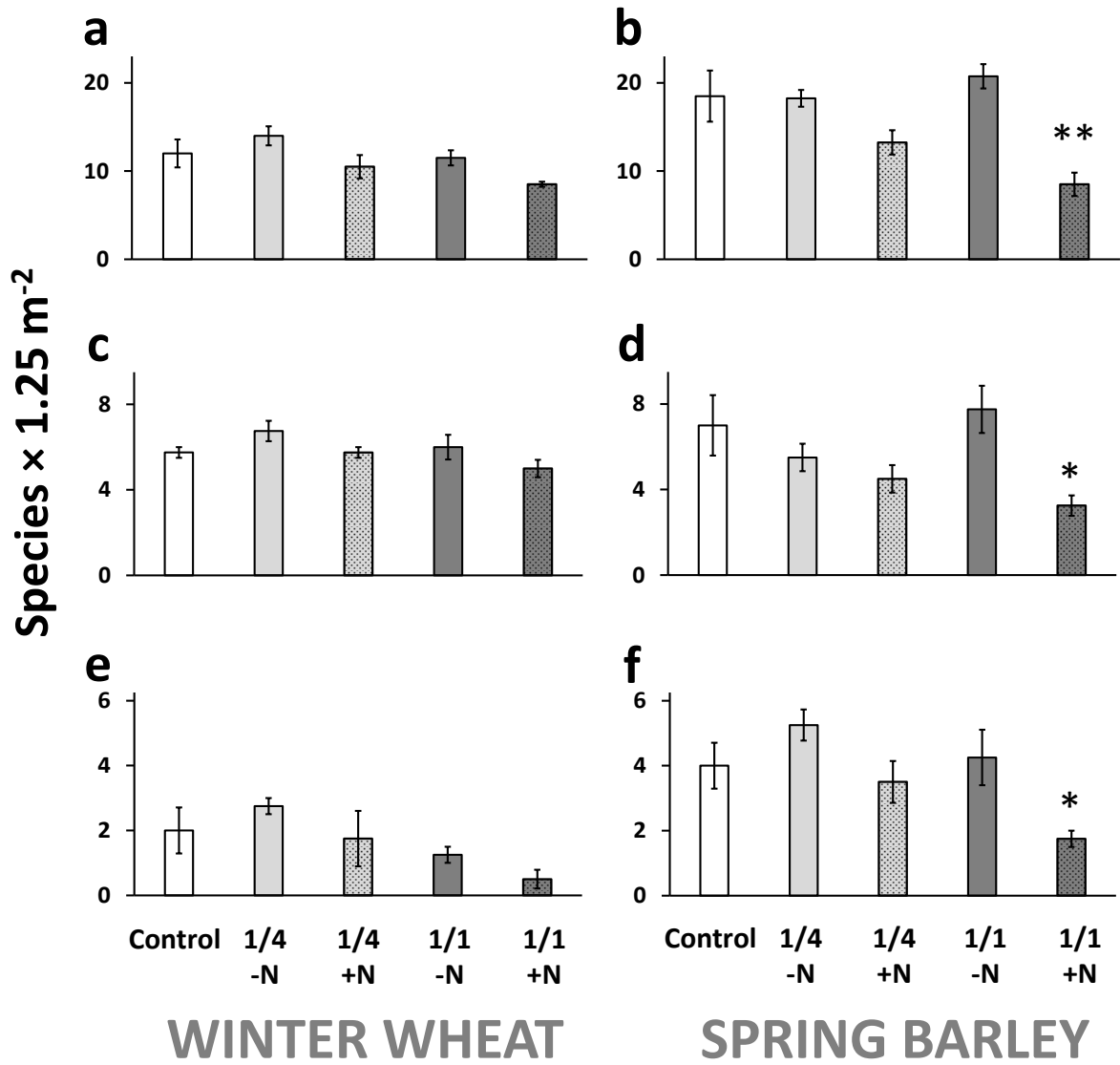
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732   (Figure 2)

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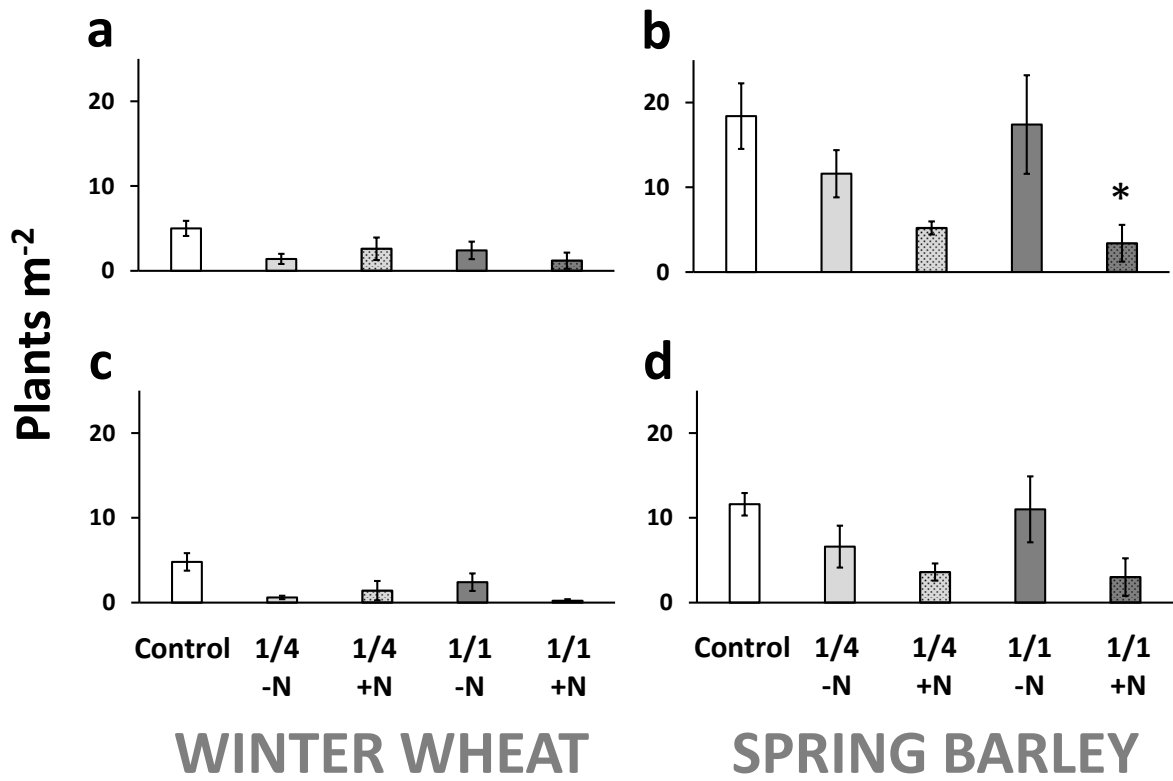
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742   (Figure 3)

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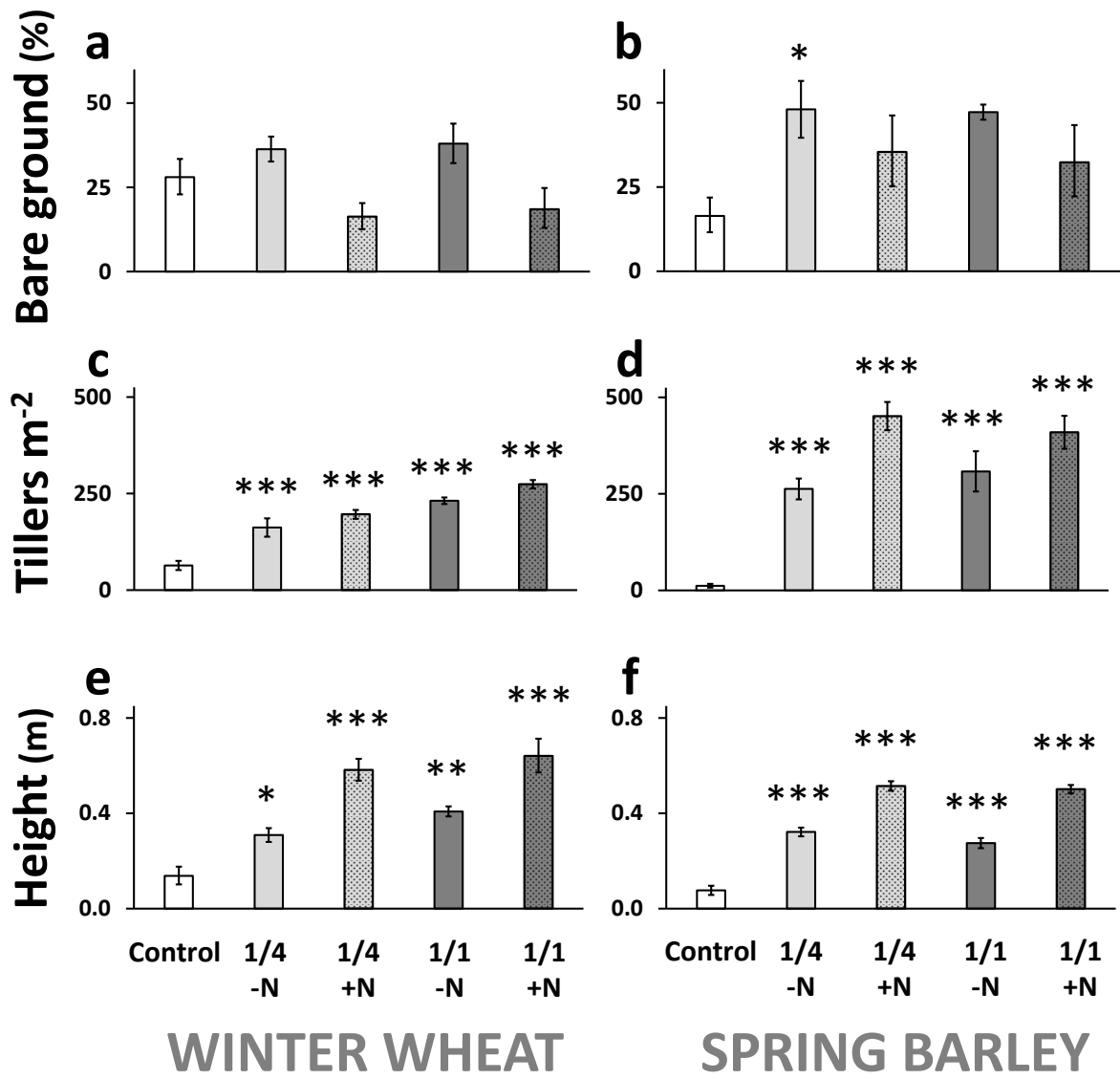
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757   (Figure 4)

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Table S1. Classification of species recorded in the winter wheat and spring barley experiments. Faunal value was assessed using three criteria, including (1) importance for insect herbivores, (2) value for insect pollinators, and (3) importance for farmland birds. Each criterion was assessed on a four-point scale: (-) = not important; (+) = of limited importance; (++) = fairly important; and (+++) = of considerable importance. Importance for insect herbivores was based on number of unique interactions in the Database of British Insects and their Foodplants (DBIF; available online at http://www.brc.ac.uk/dbif/ and accessed on 8 April 2016; see Smith and Roy 2008), with +: 6 to 20; ++: 21 to 60; and +++: ≥ 61 documented interactions. Value for insect pollinators was primarily based on nectar productivity in kg/ ha cover/ year, as reported by Baude et al. (2016), with nectar productivities of +: >20 to 80 kg/ ha cover/ year; ++: >80 to 400 kg/ ha cover/ year; and +++: > 400 kg/ ha cover/ year. When no value was reported, an *ad hoc* assessment was based on values for congeneric species. In addition, we looked at production of nutritionally valuable pollen and its utilization by various pollinators, according to a range of literature sources (Carvell et al. 2006; Hanley et al. 2008; Kleijn and Raemakers 2008). These additional pollen ratings are indicated by the superscript letter P. Importance for farmland birds was based on genus-level information collated by Holland et al. (2006), with +: genus representing >2% of the diet of at least one species in at least one life stage; ++: genus representing >10% of the diet of at least one Red-List species in at least one life stage; and +++: genus representing >10% of the diet of at least two Red-List species in at least one life stage. In addition, the genus *Fallopia*, which was not reviewed by Holland et al. (2006), was rated as fairly important (=++), as it is incorporated in farmland bird diet where locally available (Robinson 2004). Important Arable Plant Area (IAPA) species scores according to Byfield and Wilson (2005).

Species	IAPA score	Importance for insect herbivores	Value for insect pollinators	Importance for farmland birds
Species of biodiversity value:				
Capsella bursa-pastoris		++	-	+++
Cerastium fontanum		+	+	++
Chenopodium album		++	-	+++
Echium vulgare		++	+++/+[P]	
Euphorbia helioscopia		+	n/a	++
Fallopia convolvulus		+	-	++
Fumaria officinalis		+	-	++
Galium verum		++	++	-
Medicago lupulina		++	+	-
Myosotis arvensis		+	+++	+
Papaver rhoeas		+	+++[P]	-
Plantago lanceolata		+++	+[P]	-
Poa annua		+++	-	+++
Poa pratensis		++	-	+++
Polygonum aviculare		+++	-	+++
Senecio vulgaris		+++	+	++
Silene latifolia		+	++	-
Sonchus asper		+	-	++
Stellaria media		+++	-	+++
Taraxacum officinale agg.		+++	+++	++
Trifolium repens		+++	+++/++[P]	++
Tripleurospermum inodorum		++	++	-
Viola arvensis		-	+	+++

Species	IAPA score	Importance for insect herbivores	Value for insect pollinators	Importance for farmland birds
Common neutral species:				
Aethusa cynapium		+	+	-
Anagallis arvensis		-	-	-
Arenaria serpyllifolia		-	-	-
Epilobium montanum		+	-	-
Epilobium obscurum		-	-	-
Epilobium parviflorum		+	-	-
Epilobium tetragonum		-	-	-
Lapsana communis		+	-	-
Matricaria discoidea		-	+	+
Papaver dubium		-	++[P]	-
Plantago major		++	-	-
Sisymbrium officinale		++	-	-
Veronica arvensis		-	-	-
Veronica persica		-	+	-
Vulpia bromoides		-	-	-
Undesirable species:				
Alopecurus myosuroides		+	-	-
Avena fatua		+	-	-
Cirsium arvense		+++	++/+[P]	++
Cirsium vulgare		++	+++/+[P]	++
Dactylis glomerata		+++	-	-
Elytrigia repens		+++	-	-
Galium aparine		++	-	-
Rumex crispus		++	-	+++
Senecio jacobaea		+++	+++	++
Urtica dioica		+++	-	+++
Rare species:				
Anthemis cotula	7	+	n/a	-
Chaenorhinum minus	1	-	n/a	-
Euphorbia exigua	6	-	n/a	++
Fumaria densiflora	3	-	n/a	++
Fumaria parviflora	7	-	n/a	++
Kickxia elatine	2	-	n/a	-
Kickxia spuria	3	-	n/a	-
Lamium amplexicaule	1	-	(+)	+
Legousia hybrida	3	-	n/a	-
Papaver argemone	7	-	++[P]	-
Papaver hybridum	3	-	+[P]	-
Scandix pecten-veneris	9	-	n/a	+
Sherardia arvensis	1	-	-	-
Silene noctiflora	7	-	+	-

References

Baude M, Kunin WE, Boatman ND, Conyers S, Davies N, Gillespie MAK, Morton D, Smart SM, Memmott J (2016) Historical nectar assessment reveals the fall and rise of floral resources in Britain. nature 530:85-88. doi:10.1038/nature16532

Byfield AJ, Wilson PJ (2005) Important Arable Plant Areas: identifying priority sites for arable plant conservation in the United Kingdom. Plantlife International, Salisbury. http://www.plantlife.org.uk/uploads/documents/Important_Arable_Plant_Areas.pdf Accessed 20 April 2016

Carvell C, Westrich P, Meek WR, Pywell RF, Nowakowski M (2006) Assessing the value of annual and perennial forage mixtures for bumblebees by direct observation and pollen analysis. Apidologie 37:326-340. doi:10.1051/apido:2006002

Hanley ME, Franco M, Pichon S, Darvill B, Goulson D (2008) Breeding system, pollinator choice and variation in pollen quality in British herbaceous plants. Funct Ecol 22:592-598. doi:10.1111/j.1365-2435.2008.01415.x

Holland JM, Hutchison MAS, Smith B, Aebischer NJ (2006) A review of invertebrates and seed-bearing plants as food for farmland birds in Europe. Ann Appl Biol 148:49-71. doi:10.1111/j.1744-7348.2006.00039.x

Kleijn D, Raemakers I (2008) A retrospective analysis of pollen host plant use by stable and declining bumblebees. Ecology 89:1811-1823. doi:10.1890/07-1275.1

Robinson RA (2004) The diet of seed-eating birds on lowland farmland. Brit Birds 97:464-467

Smith RM, Roy DB (2008) Revealing the foundations of biodiversity: the Database of British Insects and their Foodplants. Brit Wildlife 20:17-25

Table S2. Treatment effects on non-crop vegetative cover and species richness, on establishment of sown rare species, and on vegetation structural parameters in winter wheat and in spring barley. Parameters were analysed using linear mixed models (LMM) or generalized linear mixed models (GLMM). F-values and significance levels given, significant (P < 0.05) model terms shown in bold.

Parameter	Method	Cereal sowing rate		N fertilisation		Cereal sowing × N fertilisation	
		$F_{1,9}$	P	$F_{1,9}$	P	$F_{1,9}$	P
A. Winter wheat experiment							
Non-crop vegetative cover							
All spp.	LMM	1.81	0.212	0.89	0.371	1.70	0.225
Spp. of faunal value	LMM	0.00	0.996	0.17	0.688	2.25	0.168
Rare and declining spp.	LMM	**5.64**	**0.042**	0.37	0.560	1.04	0.334
Undesirable weeds	LMM	2.95	0.120	0.12	0.741	1.20	0.302
Non-crop species richness							
All spp.	GLMM	**5.52**	**0.043**	**11.54**	**0.008**	0.01	0.935
Spp. of faunal value	GLMM	2.88	0.124	5.10	0.050	0.02	0.888
Rare and declining spp.	GLMM	**10.21**	**0.011**	4.59	0.061	0.53	0.486
Sown species establishment							
Pooled rare spp.	GLMM	0.05	0.835	0.00	0.947	1.45	0.260
Kickxia spuria	GLMM	0.10	0.762	0.83	0.386	3.44	0.096
Vegetation structure							
Bare ground	LMM	0.20	0.668	**18.36**	**0.002**	0.01	0.908
Cereal tiller density	GLMM	**20.13**	**0.002**	**5.48**	**0.044**	0.02	0.896
Vegetation height	LMM	4.96	0.053	**37.77**	**< 0.001**	1.80	0.212
B. Spring barley experiment							
Non-crop vegetative cover							
All spp.	LMM	0.93	0.360	**5.24**	**0.048**	0.21	0.660
Spp. of faunal value	LMM	0.11	0.752	3.86	0.081	1.07	0.327
Rare and declining spp.	LMM	2.42	0.154	**11.71**	**0.008**	3.16	0.109
Undesirable weeds	LMM	1.04	0.335	0.18	0.684	0.07	0.902
Non-crop species richness							
All spp.	GLMM	2.75	0.132	**40.59**	**< 0.001**	**9.04**	**0.015**
Spp. of faunal value	GLMM	0.00	0.951	**14.99**	**0.004**	**5.85**	**0.039**
Rare and declining spp.	GLMM	**6.89**	**0.028**	**14.08**	**0.004**	1.96	0.195
Sown species establishment							
Pooled rare spp.	GLMM	0.00	0.981	**9.14**	**0.014**	1.06	0.329
Kickxia spuria	GLMM	0.12	0.737	4.02	0.076	0.53	0.484
Vegetation structure							
Bare ground	LMM	0.05	0.830	2.40	0.156	0.02	0.898
Cereal tiller density	GLMM	0.09	0.769	**16.15**	**0.003**	1.56	0.243
Vegetation height	LMM	**6.83**	**0.028**	**348.60**	**< 0.001**	1.87	0.204

Table S3. Establishment of five sown rare arable species in the winter wheat and spring barley experiments. Means ± SE given for established plants per m^2.

	Treatment				
	Control	**1/4 sown, no N**	**1/4 sown, with N**	**1/1 sown, no N**	**1/1 sown, with N**
Winter wheat					
Kickxia spuria	4.8 ± 1.0	0.6 ± 0.2	1.4 ± 1.1	2.4 ± 1.0	0.2 ± 0.2
Lithospermum arvense	0	0	0	0	0
Papaver argemone	0	0.8 ± 0.8	0	0	0
Scandix pecten-veneris	0.2 ± 0.2	0	0.2 ± 0.2	0	0
Silene noctiflora	0	0	1.0 ± 1.0	0	1.0 ± 1.0
Total	**5.0 ± 0.9**	**1.4 ± 0.6**	**2.6 ± 1.3**	**2.4 ± 1.0**	**1.2 ± 1.0**
Spring barley					
Kickxia spuria	11.6 ± 1.3	6.6 ± 2.5	3.6 ± 1.0	11.0 ± 3.9	3.0 ± 2.2
Lithospermum arvense	0	0	0	0	0
Papaver argemone	6.2 ± 2.9	4.4 ± 1.0	1.0 ± 0.4	5.4 ± 1.5	0
Scandix pecten-veneris	0	0.6 ± 0.4	0.2 ± 0.2	0.4 ± 0.2	0.2 ± 0.2
Silene noctiflora	0.6 ± 0.6	0	0.4 ± 0.4	0.6 ± 0.6	0.2 ± 0.2
Total	**18.4 ± 3.9**	**11.6 ± 2.8**	**5.2 ± 0.8**	**17.4 ± 5.8**	**3.4 ± 2.2**